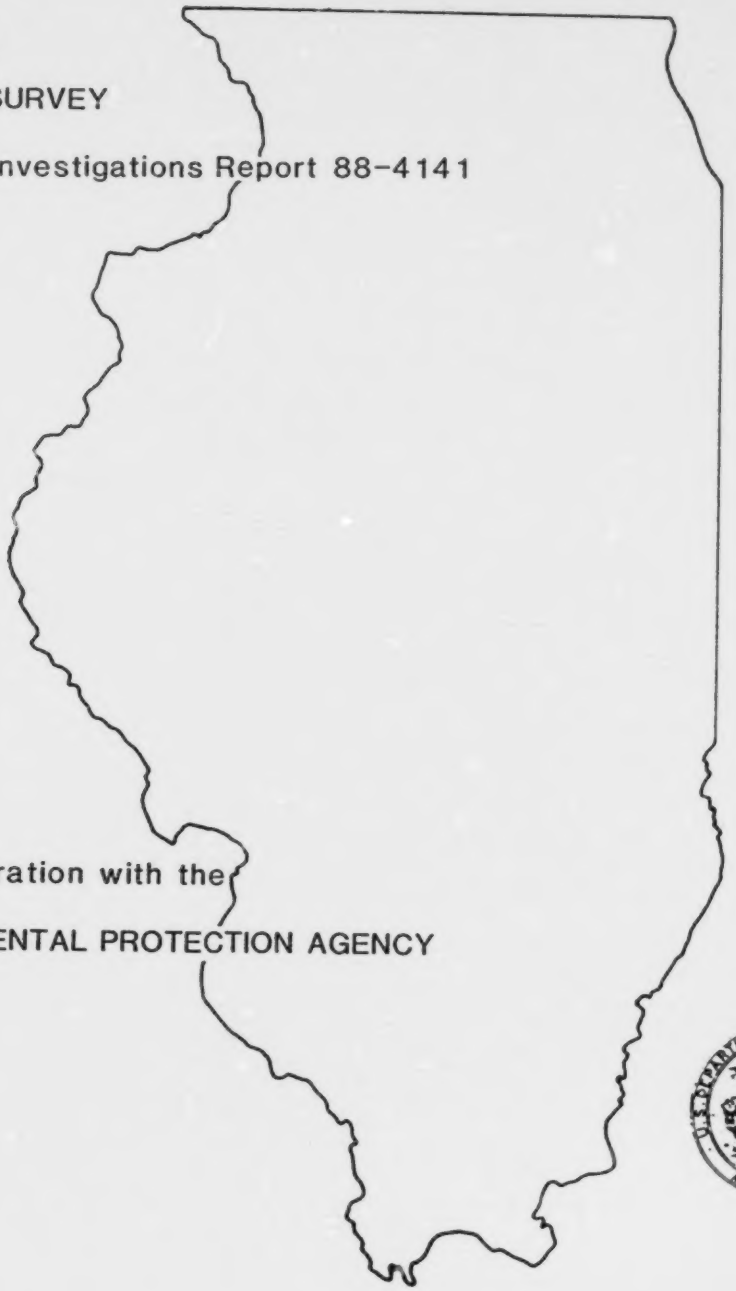
88-4141

ASSESSMENT OF PROCESSES AFFECTING LOW-FLOW WATER QUALITY OF CEDAR CREEK, WEST-CENTRAL ILLINOIS



U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4141

Prepared in cooperation with the

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

I 19.42/4:

READEX FICHE best copy available

ASSESSMENT OF PROCESSES AFFECTING LOW-FLOW WATER QUALITY OF CEDAR CREEK, WEST-CENTRAL ILLINOIS

By Arthur R. Schmidt, W. O. Freeman, and R. D. McFarlane

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4141

Prepared in cooperation with the

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

Urbana, Illinois

January 1989

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secetary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
102 E. Main St., 4th Floor
Urbana, IL 61801

Copies of this report can
be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Box 25425
Denver, CO 80225

CONTENTS

	Page
Abstract	1
Introduction	1
Purpose and scope	2
Study area	2
Acknowledgments	10
Low-flow water quality	10
Data-collection methods	10
Flow conditions	12
Water-quality conditions	14
Macroinvertebrate community	19
Assessment of processes affecting water quality	20
Description of model and application	20
Analysis of simulations	27
Flow and specific conductance	28
Hydraulics	28
Algae and nutrients	32
Dissolved oxygen	35
Simulation of hypothetical situations	55
Summary and conclusions	55
References cited	60

ILLUSTRATIONS

Figures

1-2. Maps showing:

1. Location of Cedar Creek basin in west-central Illinois.. 3
2. Location of sampling sites in the study area..... 5

3-5. Graphs showing:

3. Percentage of measurements with dissolved-oxygen concentrations less than 6 milligrams per liter during the July 9-10, 1985, diel sampling period..... 15
4. Percentage of measurements with dissolved-oxygen concentrations less than 6 milligrams per liter during the August 7-8, 1985, diel sampling period..... 17
5. Percentage of measurements with dissolved-oxygen concentrations less than 6 milligrams per liter during the August 27-28, 1985, diel sampling period... 18

ILLUSTRATIONS

Page

Figure 6. Diagram showing constituents and interactions evaluated with the QUAL-II model..... 21

7-8. Graphs showing:

7. Specific conductance at sites 8, 11, 14, and 18 on August 23-29, 1985..... 22

8. Discharge and ammonia and nitrite plus nitrate concentrations of the wastewater-treatment-facility effluent (site WWTF), August 24-28, 1985..... 23

9. Diagram showing the location of modeled subreaches of Cedar Creek relative to sampling sites and tributary locations..... 24

10-24. Graphs showing:

10. Stream discharges measured, estimated, and simulated, July 9-10 and August 7-8, 1985..... 29

11. Measured and simulated specific conductance, July 9-10 and August 7-8, 1985..... 30

12. Measured and simulated concentrations of phosphorus, ammonia nitrogen, chlorophyll-a, and nitrite plus nitrate nitrogen, July 9-10, 1985..... 38

13. Measured and simulated concentrations of phosphorus, ammonia nitrogen, chlorophyll-a, and nitrite plus nitrate nitrogen, August 7-8, 1985..... 39

14. Concentrations of phosphorus, ammonia nitrogen, dissolved oxygen, and nitrite plus nitrate nitrogen, simulated by the model with and without algae, July 9-10, 1985..... 42

15. Concentrations of phosphorus, ammonia nitrogen, dissolved oxygen, and nitrite plus nitrate nitrogen measured and simulated by the model with and without algae, August 7-8, 1985..... 43

16. Measured and simulated concentrations of ultimate carbonaceous biochemical oxygen demand and dissolved oxygen, July 9-10, 1985..... 46

17. Measured and simulated concentrations of ultimate carbonaceous biochemical oxygen demand and dissolved oxygen, August 7-8, 1985..... 47

18. Measured and simulated sediment oxygen demand..... 48

19. Concentrations of dissolved oxygen measured and simulated with and without changes in sediment oxygen demand, July 9-10 and August 7-8, 1985..... 49

20. Change in dissolved-oxygen concentration resulting from 10-percent increases in atmospheric reaeration rate, algal growth rate, carbonaceous biochemical oxygen demand decay rate, ammonia oxidation rate, and sediment oxygen demand, July 9-10, 1985..... 53

ILLUSTRATIONS

Page

Figures
10-24. Graphs showing:--Continued
21. Change in dissolved-oxygen concentration resulting from 10-percent increases in atmospheric reaeration rate, algal growth rate, carbonaceous biochemical oxygen demand decay rate, ammonia oxidation rate, and sediment oxygen demand, August 7-8, 1985..... 54
22. Concentrations of dissolved oxygen measured and simulated with and without the instream aerators, July 9-10 and August 7-8, 1985..... 56
23. Concentrations of dissolved oxygen measured and simulated with and without reduced sediment oxygen demand, July 9-10 and August 7-8, 1985..... 57
24. Concentrations of dissolved oxygen measured and simulated with and without the instream aerators and with reduced sediment oxygen demand, July 9-10 and August 7-8, 1985..... 58

TABLES

Table 1. Stream data-collection sites..... 6
2. Land uses and corresponding areas for the Cedar Creek watershed in the vicinity of Galesburg, Illinois..... 9
3. Mean and standard deviation of discharges in Cedar Creek at site 14 and from the wastewater-treatment-facility outfall during the July 9-10, August 7-8, and August 27-28, 1985, diel sampling periods and during the 4 days prior to each diel sampling period; and discharges measured at each tributary site during the same diel sampling periods..... 13
4. Macroinvertebrate biotic indices, July 11, 1985..... 19
5. Headwater, tributary, and point-source boundary conditions for the model of the August 7-8, 1985, diel sampling period..... 26
6. Incremental inflow and temperature boundary conditions for the model of the August 7-8, 1985, diel sampling period.... 27
7. Coefficients, exponents, and errors of estimate for the exponents for the equations used in the model to estimate velocity and depth from discharge..... 31

TABLES

		Page
Table 8.	Coefficients used in the model to simulate algal and nutrient kinetics	36
9.	Reach-dependent coefficients used in the model to simulate algal and nutrient kinetics	37
10.	Sensitivity analysis showing maximum change in nutrient and chlorophyll-a concentrations for the model of the July 9-10, 1985, diel sampling period, with changes in model coefficients as shown	40
11.	Sensitivity analysis showing maximum change in nutrient and chlorophyll-a concentrations for the model of the August 7-8, 1985, diel sampling period, with changes in model coefficients as shown	41
12.	Coefficients used in the model to simulate carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations	45
13.	Sensitivity analysis showing maximum change in ultimate carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for the model of the July 9-10, 1985, diel sampling period, with changes in model coefficients as shown	50
14.	Sensitivity analysis showing maximum change in ultimate carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for the model of the August 7-8, 1985, diel sampling period, with changes in model coefficients as shown	51
15.	Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period	64

CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may want to use metric (International System) units, the inch-pound values in this report may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.09290	square meter (m^2)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	3,785	cubic meter per day (m^3/d)

- -

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9 \times (°F-32)$$

SYMBOLS

A is the algae concentration, in milligrams per liter;

A_x is the mean cross-sectional area, in square feet;

C is the chlorophyll-a concentration, in micrograms per liter;

D is the mean depth of the subreach, in feet;

$\frac{d}{dt}$ is the total derivative with respect to time;

$\underline{e}$ is the base of the natural system of logarithms, having a numerical value of approximately 2.718.

I is the local light intensity, in Langleys per minute;

K_1 is the biochemical oxygen demand decay rate per day;

K_2 is the reaeration rate coefficient per day;

K_4 is the sediment oxygen demand, in milligrams per liter per foot of reach length;

K_L is the light half-saturation constant, in Langleys per minite;

K_n is the nitrogen half-saturation constant, in milligrams per liter;

K_p is the phosphorus half-saturation constant, in milligrams per liter;

L is the ultimate carbonaceous biochemical oxygen demand, in milligrams per liter;

N is the nitrite plus nitrate nitrogen concentration, in milligrams per liter;

N_1 is the ammonia concentration, in milligrams per liter;

N_2 is the nitrite concentration, in milligrams per liter;

N_3 is the nitrate concentration, in milligrams per liter;

O is the dissolved-oxygen concentration, in milligrams per liter;

O^* is the saturation concentration of dissolved oxygen, in milligrams per liter;

P is the phosphorus concentration, in milligrams per liter;

Q is the average discharge in the subreach, in cubic feet per second;

t is time, in hours;

V is the average velocity, in feet per second;

α_o is the chlorophyll-$\underline{a}$ to algae ratio, in micrograms of chlorophyll-$\underline{a}$ per milligram of algae;

α_1 is the fraction of algal biomass that is nitrogen, in milligrams nitrogen per milligram of algae;

α_2 is the fraction of algal biomass that is phosphorus, in milligrams of phosphorus per milligram of algae;

α_3 is the milligrams oxygen produced per unit of algae growth;

SYMBOLS

α_4 is the milligrams oxygen consumed per unit of algae respired;

α_5 is the milligrams of dissolved oxygen consumed per milligram of ammonia oxidized to nitrite;

α_6 is the milligrams of dissolved oxygen consumed per milligram of nitrite oxidized to nitrate;

α_d is the empirical coefficient for depth;

α_v is the empirical coefficient for the reach average velocity;

β_1 is the rate of oxidation of ammonia to nitrite, in reciprocal days;

β_2 is the rate of oxidation of nitrite to nitrate, in reciprocal days;

β_d is the empirical exponent for depth;

β_v is the empirical exponent for the reach average velocity;

λ is the light extinction coefficient, in reciprocal feet;

ρ is the algal respiration rate, in reciprocal days;

σ_1 is the algal settling rate, in feet per day;

σ_2 is the benthos source rate for phosphorus, in milligrams of phosphorus per foot per day;

σ_3 is the benthos source rate for ammonia, in milligrams of ammonia per foot per day;

μ is the growth rate for algae, in reciprocal days; and

μ_{max} is the maximum growth rate for algae, in reciprocal days.

ASSESSMENT OF PROCESSES AFFECTING LOW-FLOW WATER QUALITY OF CEDAR CREEK, WEST-CENTRAL ILLINOIS

By Arthur R. Schmidt, W. O. Freeman, and R. D. McFarlane

ABSTRACT

Water quality and the processes that affect dissolved-oxygen, nutrient (nitrogen and phosphorus species), and algal concentrations were evaluated for a 23.8-mile reach of Cedar Creek near Galesburg, west-central Illinois, during periods of warm-weather, low-flow conditions. Water-quality samples were collected and stream conditions were measured over a diel (24-hour) period on three occasions during July and August 1985.

Analysis of the data obtained indicates that iron, copper, manganese, phenols, and total dissolved-solids concentrations exceeded Illinois' general-use water-quality standards at some sample sites. Dissolved-oxygen concentrations were less than the State standard at up to 95 percent of the sampled sites during the diel sampling periods.

These data were used to calibrate and verify a one-dimensional, steady-state, water-quality model. The computer model was used to assess the relative effects on low-flow water quality of processes including algal photosynthesis and respiration, ammonia oxidation, biochemical oxygen demand, sediment oxygen demand, and stream reaeration. Results from model simulations and sensitivity analyses indicate that sediment oxygen demand is the principal cause of small dissolved-oxygen concentrations measured in the creek.

INTRODUCTION

Assessment of the effect of storm runoff on the quality of receiving streams has been the subject of many recent investigations--notably the U.S. Geological Survey National Urban Runoff Program, which began in 1978. Results from urban-runoff studies (Clarke, 1984) indicate that storm runoff has a short-lived, highly transient effect on the quality of the receiving stream. The suspended solids carried by the storm water settle to the streambed as bottom material as the flow recedes to prestorm levels. These deposits can contain elevated constituent concentrations and high oxygen demands (MacMullen, 1984). Thus, the long-term effects of storm runoff on the stream quality are the result of deposited bottom material and are most evident during warm weather, low-flow periods when water quality is most susceptible to degradation.

This report, the result of the first phase of a two-phase study by the U.S. Geological Survey in cooperation with the IEPA (Illinois Environmental Protection Agency), presents an assessment of the warm-weather, low-flow water

quality and the processes affecting it for Cedar Creek near Galesburg, Illinois. Cedar Creek was selected for this study because historical water-quality data collected by the IEPA (Ken Newman, Illinois Environmental Protection Agency, written commun., 1985) and data collected by the Galesburg Sanitary District and described in a report by Clark and others (1980) indicate that water-quality standards have not been met in some reaches of the creek. Dissolved-oxygen (DO) concentrations were as small as 0.2 mg/L (milligrams per liter)--well below the minimum concentration of 5 mg/L as given in the State general-use water-quality standard (Illinois Pollution Control Board, 1986, p. 6). In addition, iron, copper, manganese, TDS (total dissolved solids), and phenol concentrations were in excess of the maximum concentrations given in the State water-quality standards. Cedar Creek provided the opportunity to model the effect of nonpoint-source pollution on low-flow water quality because, during low-flow periods, it receives effluent from only two point sources. However, Cedar Creek receives storm runoff from a variety of nonpoint sources including urban runoff, combined-sewer overflow discharges, and runoff from agricultural land including row crops, pasture, and feed lots. These other sources may contribute significant amounts of sediment that will deposit and affect water quality after storm flow has receded to prestorm levels.

Purpose and Scope

The purpose of this report is to describe the water quality of Cedar Creek during warm-weather, low-flow periods in July and August 1985; to identify stream reaches where State general-use water-quality standards were not met; and to identify the cause-and-effect relations of processes that control water quality.

Although an objective of the study was to assess the effect of storm flows, the scope of this report is limited to low-flow, steady-state periods. For this report, steady-state is defined as those periods when the time-averaged concentration of a constituent is constant; that is, while the magnitude of a concentration may vary, it is assumed to vary around a mean value that is constant throughout the period under consideration. The shortest period considered as steady state was 5 days--1 day for sample collection and 4 days previous to allow the entire study reach to attain steady state. Four days is the approximate traveltime of a dissolved constituent through the entire study reach.

The effect of processes that control water quality were simulated and quantified by means of a computer model. Cause-and-effect relations of processes occurring in the creek were identified using results from model simulations and sensitivity analyses.

Study Area

Cedar Creek, located in west-central Illinois, is 48.5 miles long and drains 165 mi^2 (square miles) (fig. 1). This study focused on the farthest upstream 26.2-mile reach, which drains 66.9 mi^2, including one urban area

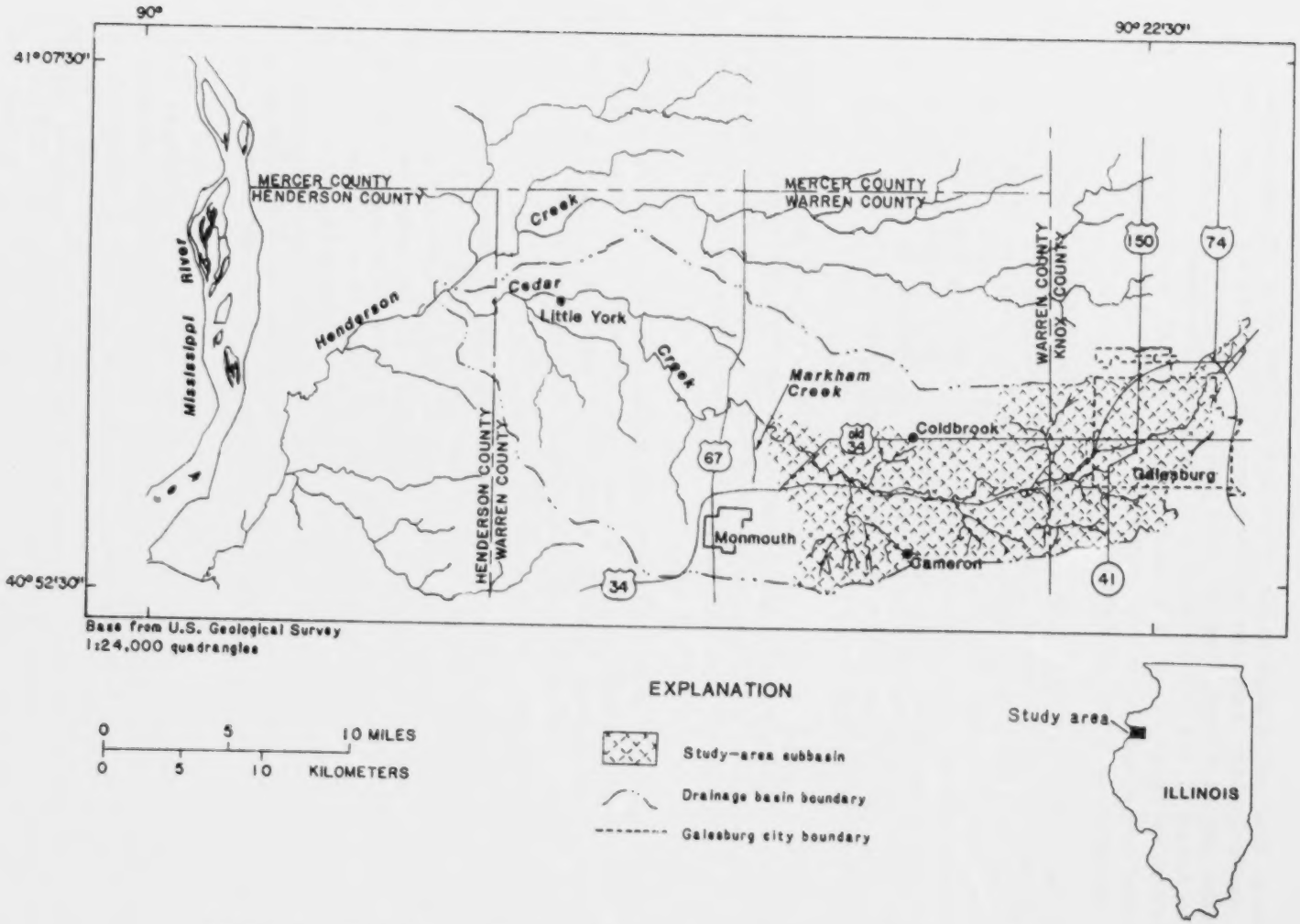


Figure 1.--Location of Cedar Creek basin in west-central Illinois.

(Galesburg) that had a population of 35,305 in 1980 (U.S. Census Bureau, 1980). Water-quality sampling stations were established at 20 locations on Cedar Creek and at 6 locations on tributaries to Cedar Creek. The sites are listed in table 1, and the locations of the sites are shown in figure 2. The land drained by Cedar Creek is primarily agricultural, consisting mainly of pasture and row crops (corn and soybeans). A detailed breakdown of the land use in the basin is given in table 2.

During this study, the IDOT (Illinois Department of Transportation) was in the process of constructing a divided, four-lane highway parallel to Cedar Creek. This construction permanently rerouted five reaches of the stream through man-made channels for distances as long as 0.36 mile. The location and configuration of these channel modifications are described by McFarlane and others (1987). Other than localized effects as a result of changes to the location of scour and deposition of sediment, the effect of these channel modifications on low-flow water quality is assumed to be the result of changes in the traveltime through the study reach.

The stream can be divided into four distinct reaches during low-flow periods. Differences between these reaches affect the water quality in that transport velocities, settling rates, atmospheric reaeration, and growth of attached periphyton and macrophytes all depend on characteristics of these reaches.

The most upstream 4.5-mile reach [headwaters to RM (river mile above mouth) 44.0] of the stream is 1 to 4 feet wide and typically less than 8 inches deep with a natural grassy channel. This reach contains a few deep pools and areas where debris accumulates, which results in very low water velocities and long traveltimes.

From RM 44.0 downstream through most of the city of Galesburg to RM 42.2, the channel is a trapezoidal or rectangular concrete section with the channel bottom being 12 to 15 feet below ground level. During low-flow conditions, the stream is about 5 feet wide and 6 inches deep in the trapezoidal sections and about 30 feet wide and 2 to 3 inches deep in the rectangular sections. The trapezoidal sections remained fairly free of debris but became choked with attached macrophytes during mid to late summer. These plants were scoured away during storm flow but grew back within a week. The mean velocity in the trapezoidal sections was about 1 ft/s (foot per second). The rectangular sections had very low velocities and extensive deposits of sand, gravel, and debris.

From RM 42.2 downstream to RM 40.2, the stream runs in a natural clay, sand, and silt-bottomed channel. In this reach, the stream is typically 10 to 15 feet wide and 4 to 12 inches deep, with mean velocities of about 0.5 ft/s. There are two pools about 2 feet deep in this reach--one extends 0.2 mile upstream from site 8 (RM 40.8) and the other extends about 0.3 mile upstream from the point of discharge from the WWTF (wastewater-treatment facility) at RM 40.2. The first pool results from a rock formation located 20 feet downstream from the gage, which serves as a low-water control. The second pool is caused by backwater from the WWTF discharge. In both pools, the mean stream

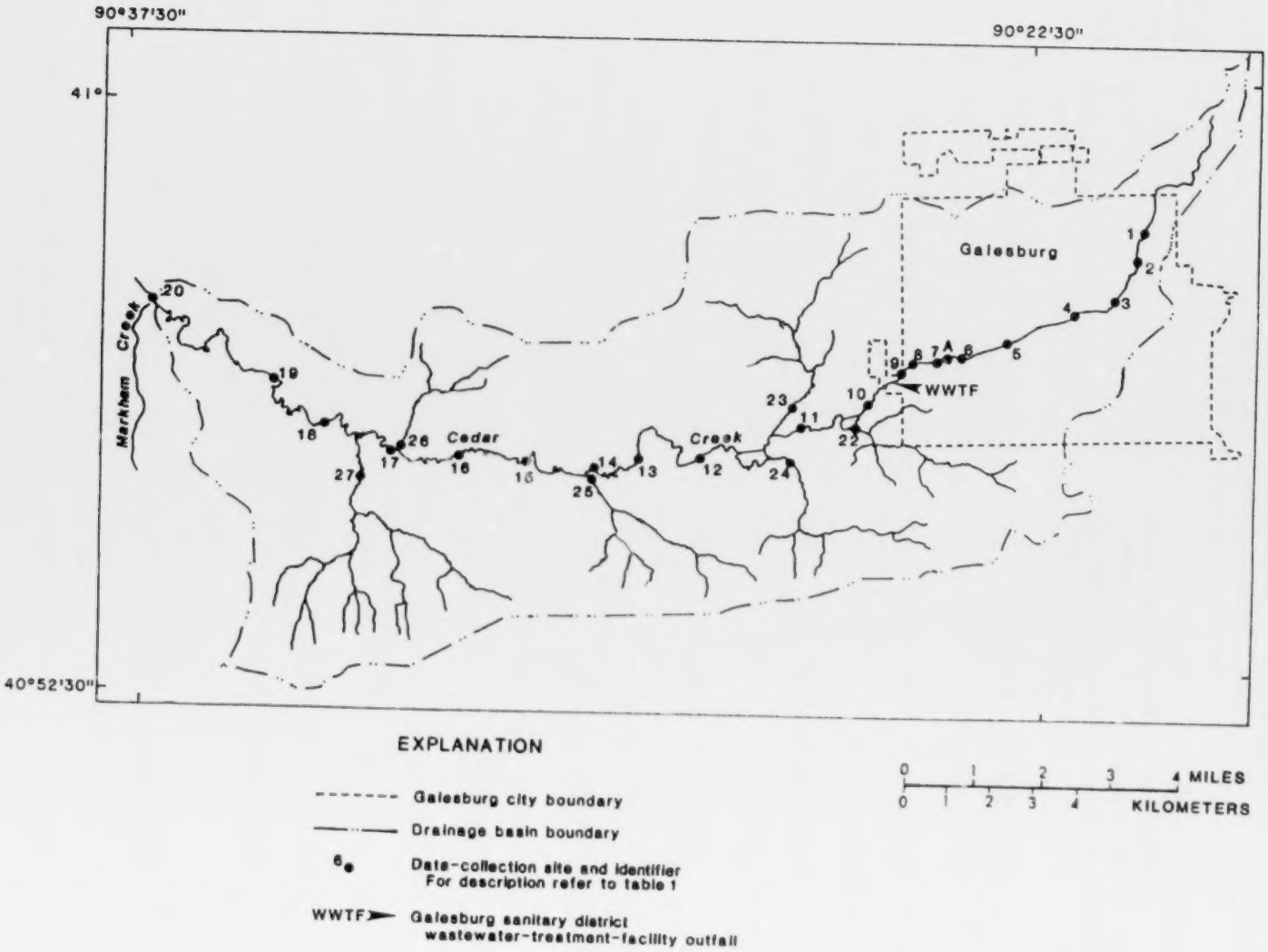


Figure 2.--Location of sampling sites in the study area.

Table 1.--Stream data-collection sites

[Site identifiers correspond to those in figure 2;
Lat, latitude; Long, longitude;
dashes indicate no data]

Site identifier	Station downstream order number	River mile above mouth	Drainage area (square miles)	Station name and location
1	05468200	45.2	2.08	Cedar Creek at Farnham Street at Galesburg Lat: 40°58'07" Long: 90°20'42"
2	05468205	44.7	2.42	Cedar Creek at Fremont Street at Galesburg Lat: 40°57'44" Long: 90°20'50"
3	05468210	44.0	2.80	Cedar Creek at Losey Street at Galesburg Lat: 40°57'17" Long: 90°21'12"
4	05468215	43.5	4.40	Cedar Creek at Chambers Street at Galesburg Lat: 40°57'10" Long: 90°21'44"
5	05468220	42.2	8.01	Cedar Creek at Henderson Street at Galesburg Lat: 40°56'46" Long: 90°23'01"
6	05468225	41.6	8.45	Cedar Creek at McClure Street at Galesburg Lat: 40°56'35" Long: 90°23'44"
A	---	41.1	---	Linwood Street storm-sewer outfall at Galesburg Lat: 40°56'33" Long: 90°24'09" (data base number 4056330902409)
7	05468230	41.1	11.2	Cedar Creek at Linwood Street at Galesburg Lat: 40°56'33" Long: 90°24'10"
8	05468240	40.8	11.6	Cedar Creek at Highway 34 at Galesburg Lat: 40°56'31" Long: 90°24'34"
9	05468245	40.5	13.8	Cedar Creek above Galesburg waste-water treatment facility at at Galesburg Lat: 40°56'25" Long: 90°24'47"

Table 1.--Stream data-collection sites--Continued

Site identifier	Station downstream order number	River mile above mouth	Drainage area (square miles)	Station name and location
WWTF	---	40.2	---	Galesburg Sanitary District wastewater treatment facility outfall at Galesburg Lat: 40°56'17" Long: 90°25'01" (data base number 4056170902501 and NPDES permit number 042)
10	05468250	39.8	14.8	Cedar Creek at Old Pickard Road near Galesburg Lat: 40°56'01" Long: 90°25'21"
11	05468265	38.1	20.2	Cedar Creek at County Line Road near Galesburg Lat: 40°55'43" Long: 90°26'28"
12	05468300	35.2	34.3	Cedar Creek near Galesburg Lat: 40°55'20" Long: 90°28'09"
13	05468305	33.1	36.4	Cedar Creek at Road 1550E near Coldbrook Lat: 40°55'20" Long: 90°29'11"
14	05468308	31.9	36.9	Cedar Creek at Road 1500E near Coldbrook Lat: 40°55'16" Long: 90°29'53"
15	05468325	30.0	45.8	Cedar Creek at Road 1400E near Coldbrook Lat: 40°55'20" Long: 90°31'03"
16	05468333	28.5	46.7	Cedar Creek at Road 1300E near Coldbrook Lat: 40°55'24" Long: 90°32'13"
17	05468349	27.0	50.7	Cedar Creek at Road 1200E near Coldbrook Lat: 40°55'30" Long: 90°33'15"
18	05468367	24.7	60.8	Cedar Creek at Road 1100E near Monmouth Lat: 40°55'50" Long: 90°34'23"

Table 1.--Stream data-collection sites--Continued

Site identifier	Station downstream order number	River mile above mouth	Drainage area (square miles)	Station name and location
19	05468375	22.7	62.0	Cedar Creek at Old Highway 34 near Monmouth Lat: 40°56'25" Long: 90°35'12"
20	05468400	19.0	66.9	Cedar Creek above mouth of Markham Creek near Monmouth Lat: 40°57'27" Long: 90°37'14"
22	05468260	[1]39.3	4.64	Cedar Creek Tributary No. 1 at Atchison, Topeka, and Santa Fe Railroad at Galesburg Lat: 40°55'42" Long: 90°25'39"
23	05468280	[1]37.7	6.98	Cedar Creek Tributary No. 2 at Road 2100N near Galesburg Lat: 40°55'58" Long: 90°26'39"
24	05468293	[1]37.0	4.52	Cedar Creek Tributary No. 3 at Atchison, Topeka, and Santa Fe Railroad near Galesburg Lat: 40°55'18" Long: 90°26'39"
25	05468316	[1]31.6	4.49	Cedar Creek Tributary No. 4 at New Highway 34 near Cameron Lat: 40°55'07" Long: 90°29'57"
26	05468341	[1]27.1	2.20	Cedar Creek Tributary No. 5 at Road 2040N near Coldbrook Lat: 40°55'32" Long: 90°33'10"
27	05468359	[1]25.8	8.53	Cedar Creek Tributary No. 6 at Road 2000N near Monmouth Lat: 40°55'07" Long: 90°33'50"

[1]River miles for the tributary sites are the location of the mouth of tributary above the mouth of Cedar Creek.

Table 2.--Land uses and corresponding areas for the Cedar Creek watershed in the vicinity of Galesburg, Illinois

Land use[1]	Area (square miles)	Percentage of basin
Cropland and pasture	53.1	79.5
Residential	4.9	7.3
Deciduous forest land	3.1	4.6
Transportation, communication, and utilities	2.3	3.4
Commercial and services	2.1	3.1
Industrial	1.0	1.5
Other urban or built-up land	.3	.4
Transitional area	.1	.2

[1] Land-use categories and areas digitized from U.S. Geological Survey (1979).

velocity falls to approximately 0.1 to 0.2 ft/s, and the streambed has extensive silt deposits. In the second pool, the streambed also has extensive sludge deposits. These may be due in part to runoff from a sludge-application field located just upstream of the WWTF and drained by a small ditch entering the creek just upstream of site 9 (RM 40.5).

The stream primarily has a natural meandering channel with a clay and silt bed from the WWTF outfall downstream to the end of the study reach. In this reach, the stream is typically 15 to 30 feet wide, 1 to 2 feet deep, and has mean velocities of 0.5 to 1 ft/s. Exceptions to this occur only where the channel is artificially modified or constrained, either by a bridge or IDOT channel modification.

Along the study reach, discharges to the creek include effluent from 1 WWTF, 6 tributaries, and 120 known sewers that carry storm runoff, at least 2 of which also carry noncontact industrial cooling water. There are 49 combined-sewer overflows that pass surcharge from the city's sanitary sewer system either directly to the stream or into one of the storm sewers. During low-flow periods, the known, measured discharges to the creek are the WWTF effluent, the tributaries, and a cooling-water discharge.

Two side-channel aeration systems, located at the point of discharge from the WWTF (RM 40.2) and at site 11 (RM 38.1), provide point sources of DO to the creek. These aeration systems withdraw a portion of the flow (from the stream at RM 38.1 and from the WWTF effluent at RM 40.2), use pure oxygen at high pressure to supersaturate the water, and then discharge the supersaturated

water to the creek through a multiport diffuser. These aeration systems are intended to increase the DO in portions of the stream where the State DO standard is not met. The DO concentration and flow rate of supersaturated water from the aerators is not known.

Acknowledgments

The authors would like to thank the city of Galesburg, Illinois, and the Galesburg Sanitary District for their extensive support in this study, including the use of their land and facilities for sampling sites and storage of equipment, and for providing maps and other necessary data. Acknowledgment also is given to the IEPA for their assistance in providing equipment and manpower, and in meeting the laboratory needs of this project.

LOW-FLOW WATER QUALITY

The data collected and water-quality processes considered in this report are for low-flow conditions, as it is these conditions that tend to result in the poorest water quality. The following section of this report presents an overview of the sampling methods used, describes the flow conditions during the sampling periods, and describes the observed water quality in terms of State water-quality standards that were not met and by means of a biologic index, which is based on macroinvertebrate populations in the creek.

Data-Collection Methods

Data measured in the creek and results from laboratory analyses of water samples were used to describe the existing water quality of the creek, to identify stream conditions that did not meet State water-quality standards, and to provide data to calibrate and verify a computer model of the creek. Details of the sample collection scheme, methods of analysis, and tables of the data are presented by McFarlane and others (1987). Data were collected during three intensive diel (24-hour) sampling periods on July 9-10, August 7-8, and August 27-28, 1985. During these periods, samples were collected at regular intervals at up to 26 locations in the creek and its tributaries and at two point-source discharges to the creek. The diel sampling was conducted during periods when stream quality and flow conditions were assumed to be steady. The 24-hour sampling period was chosen so that the variation in temperature, algae, nutrients, DO, and the resulting variation in other constituents over a diel period could be determined. Results from samples collected throughout a 24-hour period were used to calculate steady-state daily-average concentrations.

Water-quality constituents sampled for and considered in the computer model included DO (which was used as the primary indicator of water quality for quantifying various processes), dissolved ammonia, dissolved nitrite plus nitrate (throughout the report, ammonia refers to ammonia nitrogen and nitrite plus nitrate refers to nitrite plus nitrate nitrogen), dissolved phosphorus, ultimate carbonaceous BOD (biochemical oxygen demand), SOD (sediment oxygen demand), specific conductance, algal biomass (chlorophyll-a was used as an

indicator of algal biomass), water temperature, and stream discharge. Samples also were collected to determine total suspended solids; total ammonia, nitrite plus nitrate, and ammonia plus organic nitrogen (total kjeldahl nitrogen); total phosphorus; total (carbonaceous plus nitrogenous) BOD; turbidity; chemical oxygen demand; total alkalinity; total acidity; volatile suspended solids; cyanide; hardness; chloride; sulfate; fluoride; arsenic; phenol; total dissolved solids; mercury; and total and dissolved calcium, magnesium, sodium, potassium, lead, manganese, nickel, silver, barium, boron, beryllium, cadmium, strontium, vanadium, zinc, chromium, copper, cobalt, aluminum, and iron.

The validity of the assumption of steady-state conditions was checked by obtaining a 24-hour composite sample from the WWTF effluent and an industrial discharge outfall (site A) for 4 days prior to the diel sampling periods. These composite samples were analyzed to determine concentrations of ultimate carbonaceous BOD, total suspended solids, total ammonia plus organic nitrogen, and total and dissolved ammonia, nitrite plus nitrate, and phosphorus. Additionally, for the same 4 days, flow data were obtained from the WWTF and totalizing timers were installed on the two aeration systems. These data were used to estimate the magnitude and location of waters from any discharges that do not meet the steady-state approximation.

Processes that control water quality were quantified by means of a computer model. The model was calibrated to simulate the water-quality conditions measured during the July 9-10 diel sampling period. The calibrated model was verified by simulating water-quality conditions measured on August 7-8. Results from model simulations and sensitivity analyses were used to identify cause-and-effect relations of processes occurring in the creek.

Data to empirically quantify modeled processes including SOD, reaeration rates, traveltimes, and streamflow and channel characteristics were collected throughout the study period. Sediment oxygen demand was measured a total of 58 times at 38 locations in the creek from June through September 1985 and from May through September 1986. The locations, methods used, and results from these measurements are described by McFarlane and others (1987). The Illinois State Water Survey also conducted a concurrent but independent study of SOD. In their investigation, SOD was measured a total of 10 times from 7 locations (Butts, 1986).

Reaeration-rate coefficients and traveltimes were measured simultaneously using a modified-tracer technique (McFarlane and others, 1987). Reaeration-rate measurements were conducted in selected subreaches at two or more discharge rates. Reaeration-rate coefficients estimated from these data were compared with those estimated, based on measured flow characteristics, by several predictive equations (Bowie and others, 1985, p. 101-120; Rathbun, 1977). The goal of the reaeration-rate coefficient measurements was to identify the predictive equation that best estimated reaeration-rate coefficients for Cedar Creek under the low-flow conditions of this study. The equation developed by McCutcheon and Jennings (1982) to estimate reaeration based on the method presented by Velz (1970) best fit the observed data, with a correlation coefficient of 0.98 and a standard error of estimate of 1.49 per day (seven measurements). This equation was selected for use because it best fit the observed data.

Traveltime was measured as part of all reaeration-rate coefficient measurements and also was measured several times independently. Traveltime through all subreaches of the creek was measured for at least two different streamflows.

Stage data were recorded at 15-minute intervals at RM 31.9 (site 14) throughout the period of this study. These data showed the magnitude of fluctuations in discharge during the diel sampling periods and during the 4 days before these periods.

Flow Conditions

Table 3 lists the mean and standard deviation of discharge at site 14 and from the WWTF for the three diel sampling periods and for the 4 days before each diel sampling period. The tributaries with measurable discharge (sites 22-27) and their respective discharges are also listed for each diel sampling period.

Stage-discharge relations were determined from simultaneous measurements of stage and discharge at all stream and tributary sampling sites. Discharge was measured once at each sampling site during each of the diel sampling periods, and stage was measured each time a site was visited. Discharge was estimated from stage measurements by using stage-discharge relations developed for each site. All estimated discharges for the diel sampling period were averaged to estimate the average discharge at each site during the diel sampling period.

The first diel sampling was done during a period when the discharge in the creek at RM 31.9 (site 14) and from the WWTF was steady, and six of the tributaries (sites 22-27) had measurable flow at the sampling locations. Discharge measured at sites 13-16 during this period was as much as 35 percent [4.6 ft^3/s (cubic feet per second)] less than the estimated average daily discharge. This probably is because of excavation that field notes indicate was done in the stream channel just downstream from site 13 during this period.

During the second diel sampling period, discharge at RM 31.9 and from the WWTF was steady, and five of the tributaries (sites 22, 23, 24, 25, and 27) had measurable flow at the sampling locations.

During the 4 days before the August 27-28 diel sampling period, the discharge at site 14 (RM 31.9) was steady for 2 days at 9 ft^3/s, rose to a peak discharge of 64 ft^3/s 40 hours before the start of the diel data collection, and then receded to the discharge measured during the diel period. During this period, the discharge from the WWTF behaved similarly, with a maximum discharge of 24 ft^3/s and a standard deviation of 4.4 ft^3/s. All flow data from the WWTF are based on stage above a sharp-crested weir located at the entrance to the discharge pipe to the stream. Stage was measured nine times daily by personnel of the Galesburg Sanitary District, and discharge was estimated from a stage-discharge rating for the weir.

Table 3.--Mean and standard deviation of discharges in Cedar Creek at site 14 and from the wastewater-treatment-facility outfall during the July 9-10, August 7-8, and August 27-28, 1985, diel sampling periods and during the 4 days prior to each diel sampling period; and discharges measured at each tributary site during the same diel sampling periods

[Site identifers refer to those in table 1 and figures 2 and 7; ft^3/s, cubic feet per second; dashes indicate no data]

Diel sampling period						4 days previous			
Site 14		Wastewater-treatment facility				Site 14		Wastewater-treatment facility	
Mean discharge (ft^3/s)	Standard deviation discharge (ft^3/s)	Mean discharge (ft^3/s)	Standard deviation discharge (ft^3/s)	Site identifier	Measured discharge (ft^3/s)	Mean discharge (ft^3/s)	Standard deviation discharge (ft^3/s)	Mean discharge (ft^3/s)	Standard deviation discharge (ft^3/s)
July 9-10 diel sampling period									
15.7	2.5	7.3	2.4	22	0.66	15	2.4	7.2	1.8
				23	.82				
				24	.49				
				25	.66				
				26	.08				
				27	.49				
August 7-8 diel sampling period									
7.8	1.3	6.1	1.9	22	0.30	8.5	1.4	6.2	1.6
				23	.11				
				24	.02				
				25	.06				
				26	--				
				27	.04				
August 27-28 diel sampling period									
11.0	1.8	7.5	1.8	22	0.25	12.9	12.5	7.9	4.4
				23	.09				
				24	0				
				25	.02				
				26	--				
				27	.01				

Water-Quality Conditions

The primary purpose for the data collected during the diel sampling periods was to obtain data to calibrate and verify a computer model. However, these data also quantified existing water-quality conditions and identified areas where State water-quality standards were not met.

The Illinois Pollution Control Board (1986) has defined general-use water-quality standards for Illinois. These standards specify that "dissolved-oxygen concentration shall not be less than 6.0 mg/L (milligrams per liter) during at least 16 hours of any 24-hour period, nor less than 5.0 mg/L at any time." Other standards specify that copper concentrations not exceed 20 µg/L (micrograms per liter), iron concentrations not exceed 1,000 µg/L, manganese concentrations not exceed 1,000 µg/L, phenol concentrations not exceed 100 µg/L, and total dissolved-solids concentrations not exceed 1,000 mg/L. All other general-use water-quality standards evaluated in this study were met and are, therefore, not presented in this report. All data presented in the summary of this report and used in reaching the conclusions are listed in the report by McFarlane and others (1987).

During the first diel sampling period, DO concentrations ranged from 0.1 mg/L at RM 41.6 (site 6) to 19.9 mg/L at RM 43.5 (site 4). Dissolved-oxygen concentrations fell below the minimum specified by State water-quality standards at all Cedar Creek sites except at RM 39.8 (site 10). Figure 3 shows the percentage of the measurements at each site that had a DO concentration less than 5.0 and less than 6.0 mg/L. Based on the assumption that sampling frequency was uniform during the diel sampling period, the requirement that DO concentration be greater than 6.0 mg/L for 16 hours out of any 24-hour period is met only if fewer than 33 percent of the measured DO concentrations are less than 6.0 mg/L. This assumption was checked by determining the number of hours that DO concentration was less than 6.0 mg/L at all sites where more than 33 percent of the samples had DO concentrations less than 6.0 mg/L. During the first diel sampling period, this analysis indicated that the State DO standard was not met at sites at RM 38.1, RM 24.7, and RM 19.0 (sites 11, 18, and 20) although DO concentrations at these sites were never less than 5.0 mg/L. The State DO standard was not met at 95 percent of the sites sampled during the first diel sampling period.

During the first diel sampling period, iron concentrations in the creek ranged from 90 µg/L at RM 42.2 (site 5) to 2,300 µg/L at RM 27.0 (site 17). The largest iron concentration measured (2,500 µg/L) was in the tributary that enters the creek at RM 37.0 (site 24). Cedar Creek sites at RM 42.2, RM 31.9, RM 30.0, RM 28.5, RM 27.0, and RM 24.7 (sites 5, 14, 15, 16, 17, and 18) and tributaries entering the creek at RM 37.7, RM 37.0, RM 31.6, and RM 27.1 (sites 23, 24, 25, and 26) exceeded the State maximum concentration of 1,000 µg/L.

Copper concentrations in the creek ranged from less than the analytical detection limit (5.0 µg/L) at 35 percent of the Cedar Creek sites and 83 percent of the flowing tributary sites to 23 µg/L at RM 39.8 (site 10). The State standard (20 µg/L) was exceeded only at RM 39.8 (site 10).

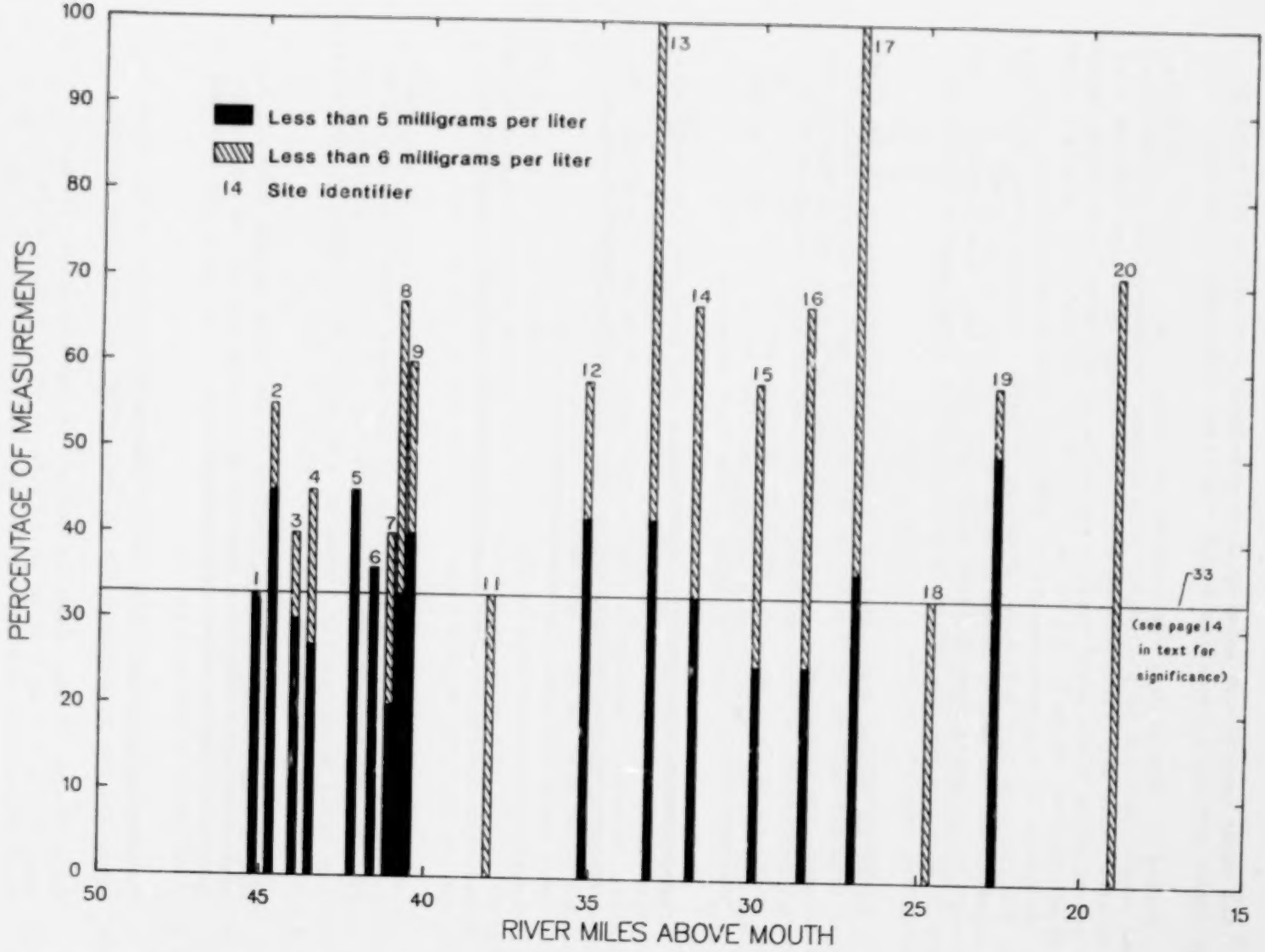


Figure 3.--Percentage of measurements with dissolved-oxygen concentrations less than 6 milligrams per liter during the July 9-10, 1985, diel sampling period.

All other general-use water-quality standards were met at all sites in Cedar Creek and its tributaries during the first diel sampling period.

During the second diel sampling period (August 7-8, 1985), DO concentrations ranged from 2.2 to 23.0 mg/L; both extreme concentrations were measured at RM 41.6 (site 6). Dissolved-oxygen concentrations were less than the minimum specified by State water-quality standards at all Cedar Creek sites except those at RM 39.8, RM 24.7, and RM 19.0 (sites 10, 18, and 20). Figure 4 shows the percentage of the measurements at each site with DO concentration less than 5.0 and less than 6.0 mg/L. These percentages indicated that the State DO standard was not met at sites at RM 40.8 and RM 27.0 (sites 8 and 17), although DO concentrations at these sites were never less than 5.0 mg/L. The State DO standard was not met at 76 percent of the sites sampled during the second diel sampling period.

During the second diel sampling period, iron concentrations in the creek ranged from 240 µg/L at RM 39.8 (site 10) to 2,700 µg/L at RM 44.0 (site 3). The largest iron concentration (3,700 µg/L) was again from the tributary that enters the creek at RM 37.0 (site 24). Iron concentrations measured at Cedar Creek sites at RM 44.0, RM 28.5, RM 27.0, RM 24.7, and RM 22.7 (sites 3, 16, 17, 18, and 19) and tributaries entering the creek at RM 37.7, RM 37.0, and RM 25.8 (sites 23, 24, and 27) exceeded the State standard.

Copper concentrations in the creek ranged from less than the analytical detection limit (5.0 µg/L) at 24 percent of the Cedar Creek sites and all tributary sites with measurable flow to 23.0 µg/L at RM 33.1 (site 13). The maximum concentration of 20 µg/L allowed by State water-quality standards was exceeded at RM 39.8, RM 33.1, and RM 27.0 (sites 10, 13, and 17).

Manganese concentrations in the creek ranged from 41 µg/L at RM 41.6 (site 6) to 860 µg/L at RM 44.0 (site 3). The maximum concentration allowed by State water-quality standards (1,000 µg/L) was exceeded in the tributary entering the creek at RM 25.8 (site 27).

Phenol concentrations in the creek ranged from less than the analytical detection limit (5.0 µg/L) at 41 percent of the Cedar Creek sites and three tributary sites to 20 µg/L at RM 22.7 (site 19). The maximum concentration allowed by State water-quality standards (100 µg/L) was exceeded in the tributary entering the creek at RM 25.8 (site 27).

Total dissolved-solids concentrations in the creek ranged from 691 mg/L at RM 38.1 (site 11) to 1,120 mg/L at RM 42.2 (site 5). The maximum concentration allowed by State water-quality standards (1,000 mg/L) was exceeded at RM 42.2 and RM 41.6 (sites 5 and 6).

All other general-use water-quality standards were met at all sites in Cedar Creek and its tributaries during the second diel sampling period.

During the third diel sampling period, DO concentrations measured in the creek ranged from 3.3 mg/L at RM 41.6 (site 6) to 13.8 mg/L at RM 39.8 (site 10). Dissolved-oxygen concentrations remained greater than 5.0 mg/L at all Cedar Creek sites except the one at RM 41.6 (site 6). Figure 5 shows the percentage of the measurements at each site with DO concentrations less than

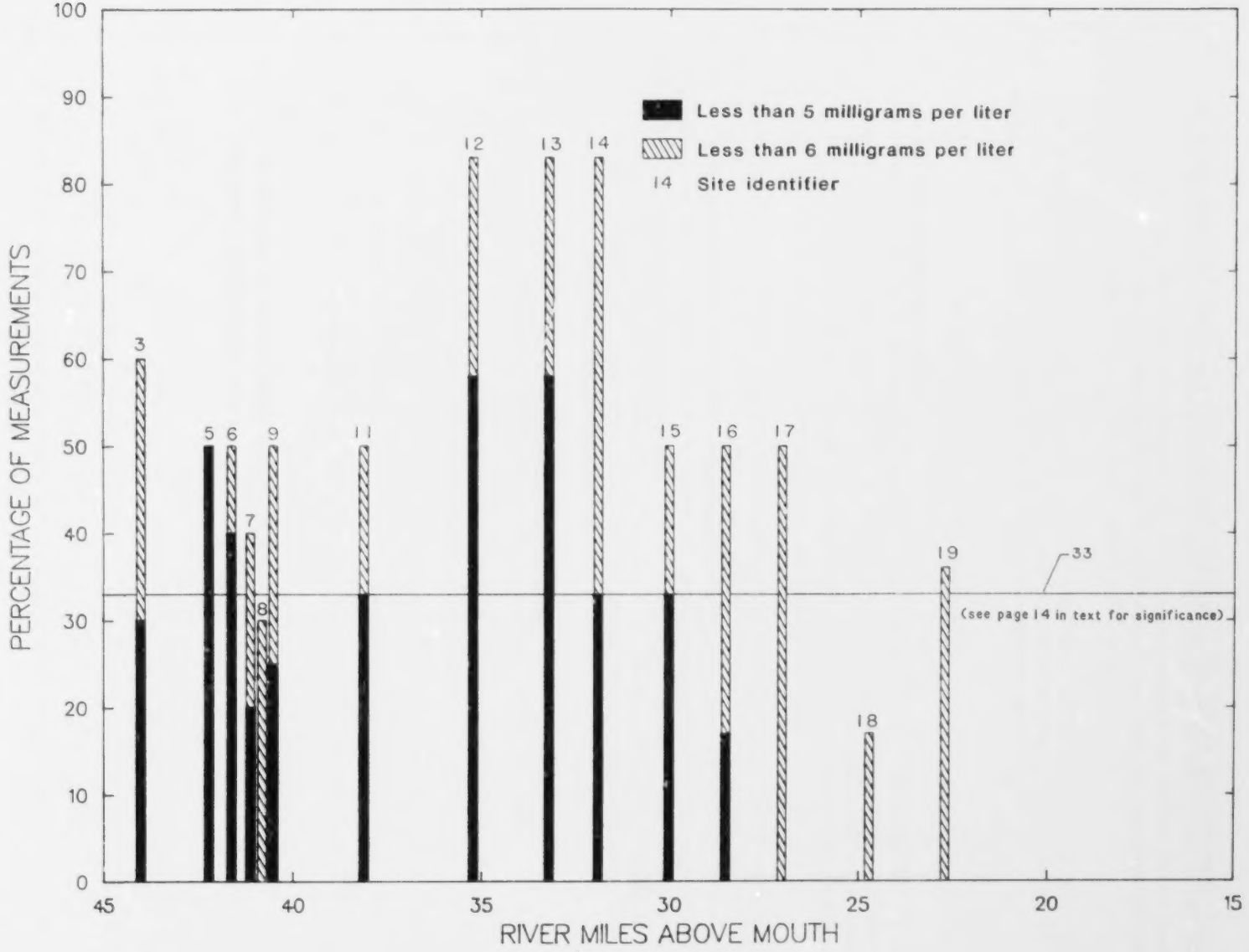


Figure 4.--Percentage of measurements with dissolved-oxygen concentrations less than 6 milligrams per liter during the August 7-8, 1985, diel sampling period.

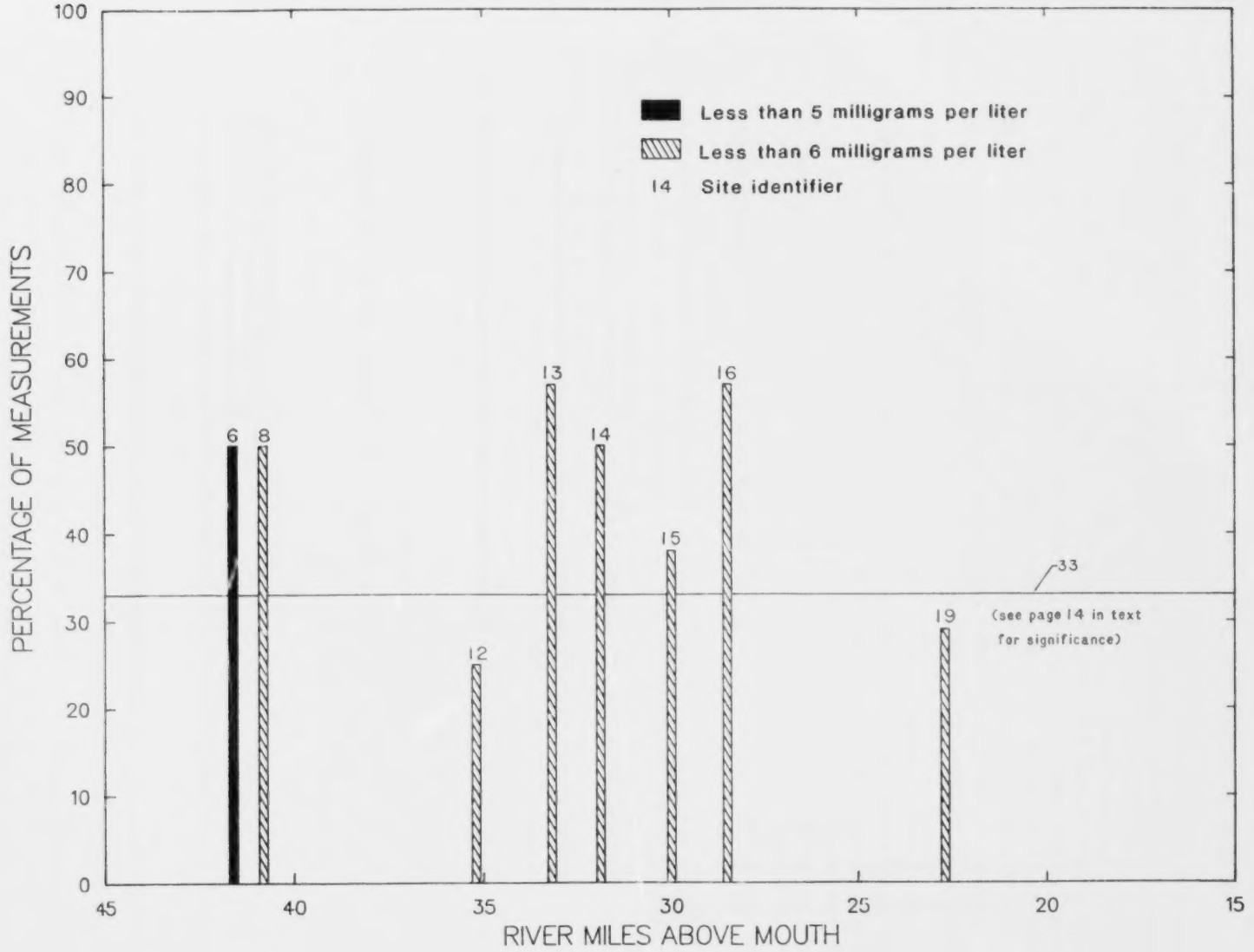


Figure 5.--Percentage of measurements with dissolved-oxygen concentrations less than 6 milligrams per liter during the August 27-28, 1985, diel sampling period.

5.0 and less than 6.0 mg/L. In the third diel period, these percentages indicated that the State DO standard was not met at sites at RM 33.1, RM 30.0, and RM 28.5 (sites 13, 15, and 16), although DO concentrations at these sites were never less than 5.0 mg/L. The State DO standard was not met at 36 percent of the sites sampled during the third diel sampling period.

Samples collected during the third diel sampling period were not analyzed for metals, total dissolved solids, or phenol concentrations. Therefore, no comparison can be made with State water-quality standards.

Macroinvertebrate Community

On July 11, 1985, a biological survey was conducted by the IEPA at 13 of the Cedar Creek diel sampling sites in order to provide an additional assessment of the water quality of the creek. Benthic macroinvertebrates were used as an indicator of the condition of the stream environment because of their restricted mobility and their sensitivity to contaminants.

The macroinvertebrate samples were collected to quantify the abundance of each species and to determine the MBI (macroinvertebrate biological index) for each site, which is the average of the pollution tolerance index for all species, weighted by the relative abundance of each species. The MBI can range from 0 to 11; larger values indicate more contaminated water. An explanation of MBI and the calculation method are described in detail by Schaeffer and others (1985). Table 4 lists the sites at which macroinvertebrate sampling was conducted and the MBI determined.

Table 4.--Macroinvertebrate biotic indices, July 11, 1985

[Site identifiers refer to those in table 1;
MBI, macroinvertebrate biotic index]

Site identifier	River mile	MBI [1]	Site identifier	River mile	MBI [1]
1	45.2	7.4	11	38.1	7.4
2	44.7	7.4	12	35.2	6.4
3	44.0	6.7	15	30.0	4.9
5	42.2	7.6	18	24.7	4.7
7	41.1	7.5	19	22.7	4.7
9	40.5	9.9	20	19.0	5.0
10	39.8	9.1			

[1] MBI data from William Ettinger, Illinois Environmental Protection Agency, written commun., November 1986.

The MBI values for Cedar Creek indicate the most contaminated water (based on the proportion of the macroinvertebrate community that are "pollution-tolerant" species) was at site 9 (RM 40.5), which is 0.3 mile upstream from the WWTF outfall. The large MBI value at this site probably is the result of the extensive sludge deposits at this site--deposits that may be the result of run-off from a sludge-application field located just upstream of site 9. Upstream from this site, values for the MBI also were large, although not as severe as at site 9. The MBI values decreased with distance downstream from the WWTF. The MBI value at site 11 (RM 38.1) indicated water quality similar to that at sites 1, 2, 3, 5, 7, (RM 45.2 to RM 41.1). The MBI values at sites 15, 18, 19, and 20 (RM 30.0 to RM 19.0) indicated the water was less contaminated than the rest of the study reach and that water quality remained nearly constant from site 15 downstream through the end of the study reach at site 20.

ASSESSMENT OF PROCESSES AFFECTING WATER QUALITY

Processes that affect water quality were quantified by means of a computer model calibrated to simulate the conditions observed in the creek. The model was calibrated to simulate the conditions measured during the July 9-10 diel sampling period. The model then was verified against the data collected during the August 7-8 diel sampling period. Results from sensitivity analyses done on the calibrated and verified models and from simulated hypothetical conditions were used to quantify the affects of processes that affect water quality. The following section of the report describes the computer model of the creek, the calibration, verification, and sensitivity analysis processes, the hypothetical simulations performed, and the assessment of the factors affecting water quality.

Description of Model and Application

The QUAL-II, one dimensional, steady-state, water-quality model (National Council of the Paper Industry for Air and Stream Improvements, 1982) was used to simulate DO and the processes affecting it. In addition to DO, the model was used to simulate ultimate carbonaceous BOD, SOD, ammonia, nitrite plus nitrate, phosphorus, algae (as chlorophyll-a), and specific conductance. Figure 6 shows the constituents and their interactions as simulated by the model. The mathematical basis of the model and details of the equations used to simulate these constituents are presented in the user's guide (National Council of the Paper Industry for Air and Stream Improvement, 1982).

On August 24, a storm passed over the study area dropping 0.65 inch of rain between 10:15 a.m. and 8:10 p.m. The runoff from this storm is characterized by specific conductance values lower than those normally measured in the study reach. Figure 7 shows a decrease in specific conductance at four sites as a result of the storm. In addition, from 4:00 to 7:00 p.m. on August 25, the Galesburg WWTF discharged at a rate of 23.5 ft^3/s, compared to the average rate of 7.8 ft^3/s for the 6-day period August 23-28. Data to characterize the specific conductance of this release were not collected. Ammonia and nitrite plus nitrate concentrations from laboratory analyses of

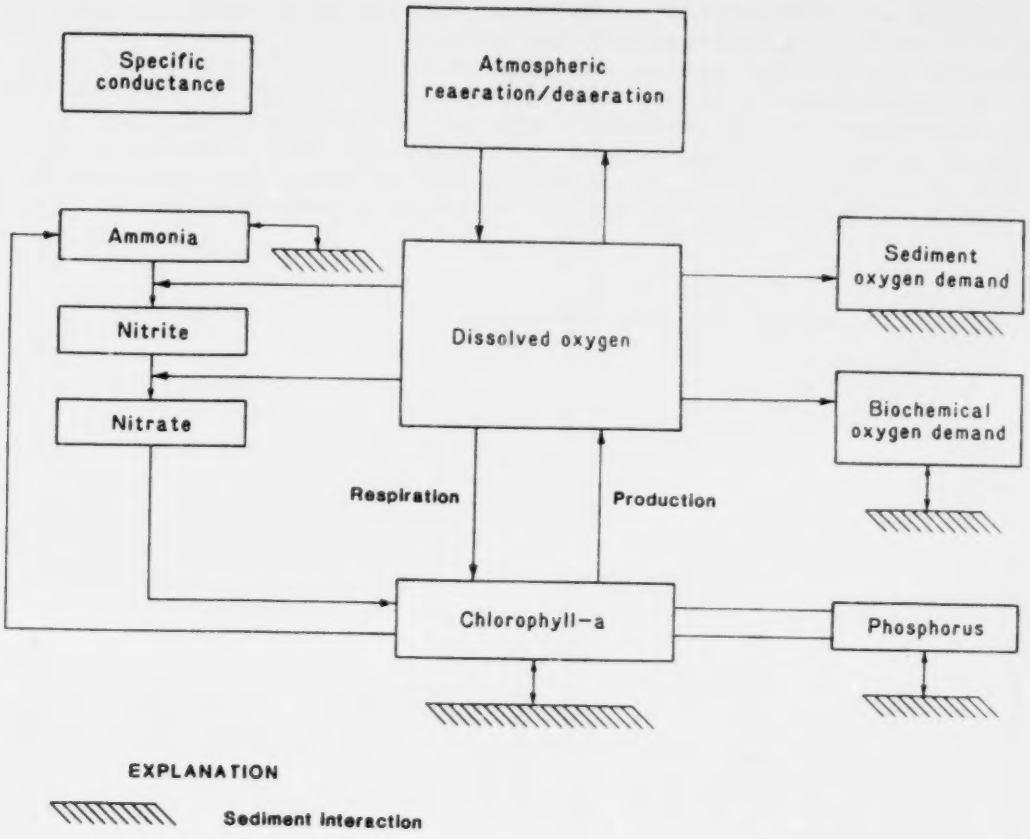


Figure 6.--Constituents and interactions evaluated with the QUAL-II model.

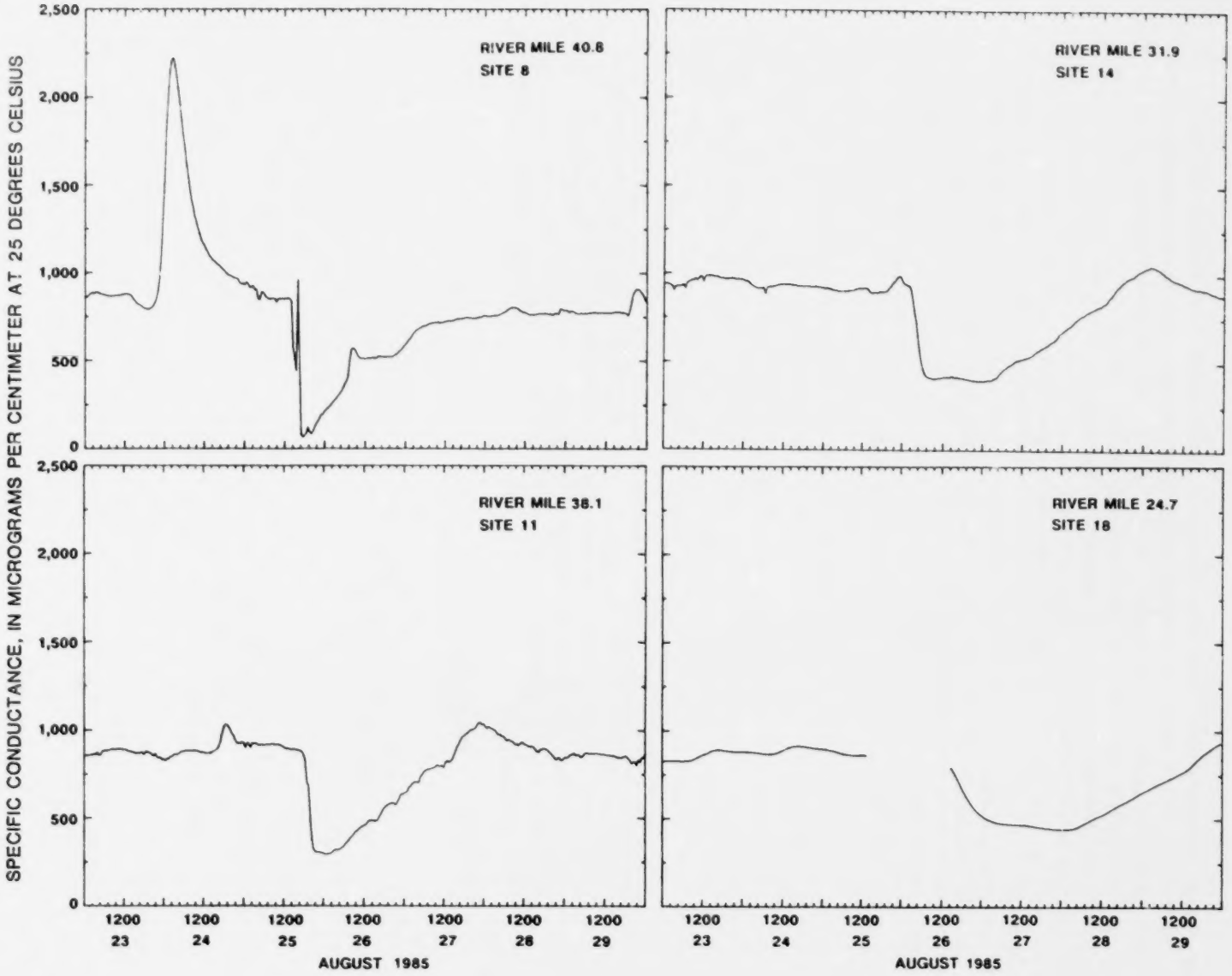


Figure 7.--Specific conductance at sites 8, 11, 14, and 18 on August 23-29, 1985.

24-hour composite samples collected from this effluent are shown in figure 8 along with the discharge rates from the WWTF. The resultant effect of the storm and the release from the WWTF was water with relatively low specific conductance, ammonia, and nitrite plus nitrate concentrations. The location of these waters was estimated, from relations between velocity and discharge, to be from site 12 (RM 35.2) to the downstream end of the study reach at the start of the third diel sampling period. The assumption of steady-state conditions is not met during the third diel sampling period because of the effect of the storm and the unusually high discharge rate from the Galesburg WWTF. For this reason, data from this period will not be included in the modeling part of the study.

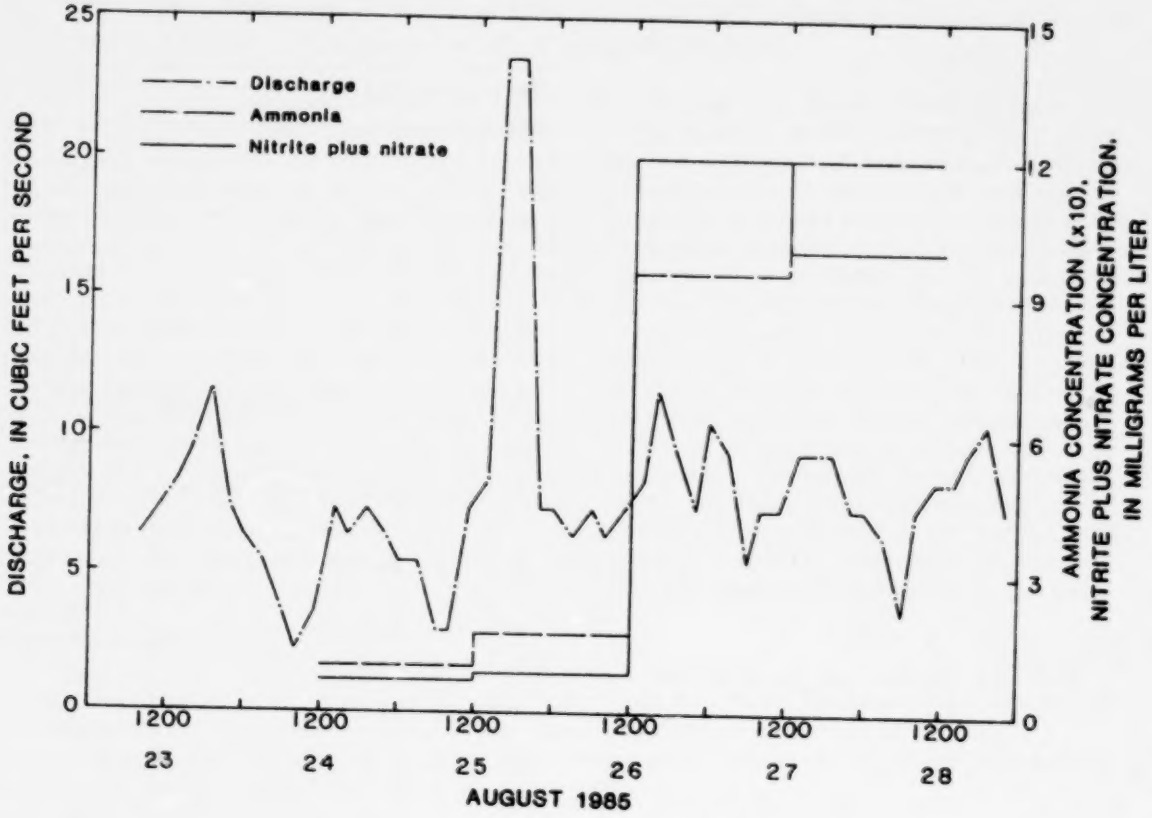


Figure 8.--Discharge and ammonia and nitrite plus nitrate concentrations of the wastewater-treatment-facility effluent (site WWTF), August 24-28, 1985.

The study reach was initially conceptualized as 27 subreaches, with subreach boundaries at sampling stations and tributary locations (fig. 9). The upstream six subreaches (RM 45.2 to RM 41.6) were not included in the calibrated model because data for these subreaches were not sufficient to define model coefficients.

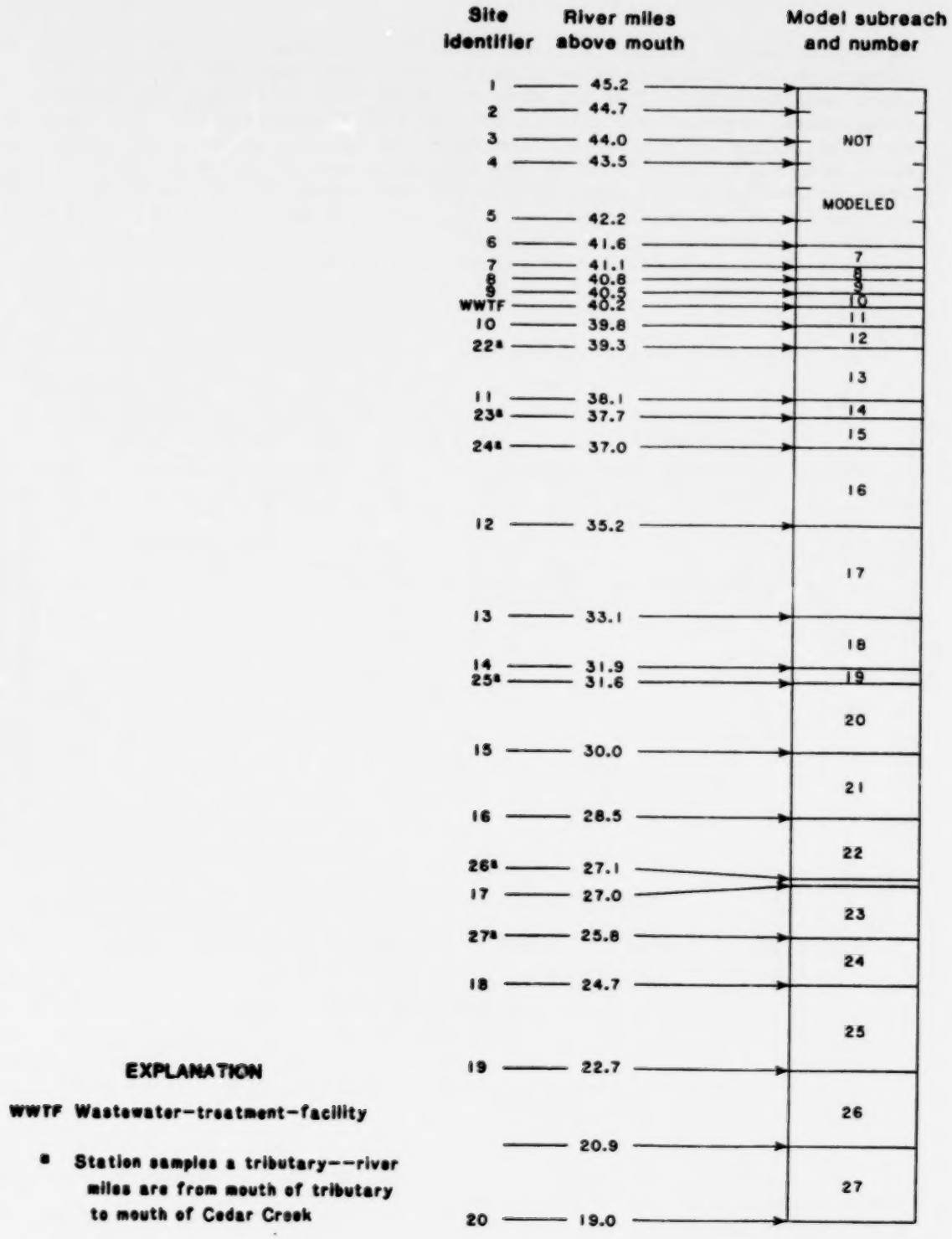


Figure 9.--Location of modeled subreaches of Cedar Creek relative to sampling sites and tributary locations.

Boundary conditions for the model are the flow and constituent concentrations from upstream of the modeled reach, from tributaries and point sources, and from base flow. Boundary conditions also include the mean temperature measured in each subreach of the model.

The aeration systems at RM 40.2 and RM 38.1 were simulated as point withdrawals of 1 ft^3/s in one computational element, with the same flow discharged as a point source one computational element (0.1 mile) downstream. The return flow had all constituent concentrations identical to the withdrawal with the exception of DO, which was raised to 55 mg/L. The withdrawal value and the DO concentration of the return flow were estimated based on calibration to DO concentrations measured just upstream and downstream from the aerator at RM 38.1 during the August 7-8 diel sampling period. The same values were used for the July 9-10 and August 7-8 diel sampling periods.

The model was calibrated by initially setting all known coefficients to the value determined from measurements of the creek. Model coefficients that were not measured but are known (stoichiometric ratios and temperature correction coefficients) were set to the appropriate value. Temperature was not simulated by the model, but the mean value from all measurements in each model subreach were used in the model for temperature-dependent calculations. The reaeration equation (McCutcheon and Jennings, 1982) was added to the model to calculate reaeration-rate coefficients based on velocities and depths determined by the model. Coefficients not yet specified were then input, using median values from literature-specified ranges (Bowie and others, 1985). These latter coefficients were adjusted, over the range given in the literature, to calibrate the model so that simulated constituent concentrations agreed with those measured from stream-water samples. The coefficients adjusted to calibrate the model were those describing nonpoint discharge, algae maximum growth, respiration, and settling rates; light extinction coefficients; nitrogen and phosphorus content of algae; the rate of oxidation of ammonia to nitrate; the benthos source rate for phosphorus; rates of oxygen production and consumption by algae growth and respiration; and sediment oxygen demand rates.

After the model was calibrated, it was verified by simulating the data from the August 7-8, 1985, diel sampling period. The changes to point source, headwater, and tributary inputs for this simulation are listed in table 5. The changes in incremental inflow and temperature in each subreach for this simulation are listed in table 6.

Sensitivity analyses were performed on the models of the water quality measured during the July 9-10 and August 7-8 diel sampling periods. Sensitivity analyses indicate the relations between model errors and uncertainty in model coefficients by giving the changes in model results (sensitivity) to changes in individual coefficients. Sensitivity analyses were performed by varying selected coefficients by the standard deviation of the measured coefficients or by varying the value over the range suggested in the literature (Bowie and others, 1985). Changes in model results caused by these changes indicate sensitivity of the model to errors in the given coefficient.

Table 5.--Headwater, tributary, and point-source boundary conditions for the model of August 7-8, 1985, diel sampling period

[Site number correspond to those in figures 2 and 9 and table 1 of this report; RM, river miles above mouth; ft^3/s, cubic feet per second; °F, degrees Fahrenheit; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; µg/L, micrograms per liter]

Site identifier	Location (RM)	Discharge (ft^3/s)	Temperature (°F)	Dissolved oxygen (mg/L)	Oxygen demand, biochemical carbonaceous, ultimate (mg/L)	Specific conductance (µS/cm)	Chlorophyll-a (µg/L)	Ammonia (mg/L)	Nitrite plus nitrate (mg/L)	Phosphorus (mg/L)
					Headwaters					
6	41.6	0.46	76.5	13.7	8.24	867	3.36	0.12	0.19	0.06
					Tributaries					
22	39.3	.30	74.3	8.3	5.9	776	4.13	.10	2.3	.08
23	37.7	.11	75.7	7.4	6.6	453	2.98	.12	3.7	.08
24	37.0	.04	73.6	4.7	10.5	644	10.6	1.2	5.6	.24
25	31.6	.06	73.0	9.2	7.5	561	3.22	.01	6.5	.05
26	27.1	0	--	--	--	--	--	--	--	--
27	25.8	.09	77.0	7.3	4.7	584	6.50	.09	2.0	.08
					Point Sources					
A	41.1	.08	67.4	6.3	9.8	587	.64	.10	.79	.02
WWTP	40.2	6.1	72.7	12.0	47.5	1,010	2.59	1.7	8.1	4.78

Table 6.--Incremental inflow and temperature boundary conditions for the model of the August 7-8, 1985, diel sampling period

[ft^3/s, cubic feet per second; °F, degrees Fahrenheit]

Subreach model	Incremental inflow (ft^3/s)	Temperature (°F)
7	0	74.0
8	.05	71.0
9	0	71.0
10	.37	72.0
11	.04	73.0
12	.05	73.6
13	.13	73.6
14	.04	75.0
15	.08	75.0
16	.19	75.0
17	.21	76.0
18	.14	75.4
19	.01	75.5
20	.07	75.5
21	.06	75.3
22	.06	74.3
23	.05	74.4
24	.05	74.4
25	.09	74.3
26	.08	74.2
27	.08	74.2

Analysis of Simulations

First the model was calibrated for discharge and specific conductance; then, chlorophyll-*a* and nutrients (phosphorus, ammonia, nitrite, and nitrate) were calibrated to match measured values; and, finally, DO was calibrated to match the measured concentrations. Discharge was calibrated using nonpoint inflow equally distributed throughout subreaches where simulated streamflow was lower than measured. Specific conductance was assumed to be conservative and was used in mass-balance calculations to check the validity of the flow modeling. Following this, chlorophyll-*a* concentrations were calibrated by adjusting settling rates and chlorophyll-*a* to algae ratios. Nutrients were calibrated by adjusting reaction coefficients, uptake by algae, and rates of settling to the streambed. Ultimate carbonaceous BOD was calibrated using

reentrainment from the streambed. Finally, DO was calibrated by adjusting SOD terms in each model subreach. A complete list of the input to the calibrated model is given in table 15 at the end of the report. The following section describes the calibration, verification, and sensitivity analysis process for each of these constituents.

Flow and Specific Conductance

Discharge, the first stream characteristic calibrated, was initially simulated using measured discharge rates from the upstream boundary, the tributaries, and point sources. Where simulated discharge was less than that estimated from stage measurements, an equally distributed, nonpoint inflow was added to the subreach. This nonpoint inflow was assumed to have specific conductance, ammonia, nitrite plus nitrate, phosphorus, ultimate carbonaceous BOD, and DO concentrations equal to the discharge-weighted average of all the tributaries. Figure 10 shows the discharges measured in the creek, those estimated from stage-discharge relations, and those simulated by the model for the July 9-10 and August 7-8, 1985, diel sampling periods.

Conservative constituents are those that do not decay and are only affected by imports, exports, and dilution. Simulation of conservative constituents can indicate incorrect flow calibration; concentrations that are larger or smaller than the measured values can indicate too much or too little dilution.

Specific conductance was assumed to be a conservative constituent. Specific conductance was measured at all stream sites and at all known inflows to the creek. Specific conductance of all nonpoint inflows to the creek was assumed to equal the discharge-weighted average of all the tributaries entering the creek. Figure 11 shows the specific conductance measured in the creek and simulated by the model for the July 9-10 and August 7-8, 1985, diel sampling periods.

Sensitivity analyses for flow were performed by varying the flow from the point sources by 25 percent, which corresponds to the standard deviation of the WWTF discharge from its mean value. The effect caused by this variation was negligible. The largest effect on the specific conductance mass balance was at site 20 (RM 19.0), where the specific conductance varied from 804 to 812 µS/cm (microsiemens per centimeter at 25 degrees Celsius) for the model of the first diel period and from 888 to 913 µS/cm for the model of the second diel period.

Hydraulics

Velocity is an important factor in model simulations of nonconservative constituents because it affects the residence time and, thus, the change in constituent concentrations that may occur in a subreach. Velocity also determines the location of extreme constituent concentrations. Velocity was simulated using empirical coefficients in the following equation:

$$V = \alpha_v Q^{\beta_v} . \qquad (1)$$

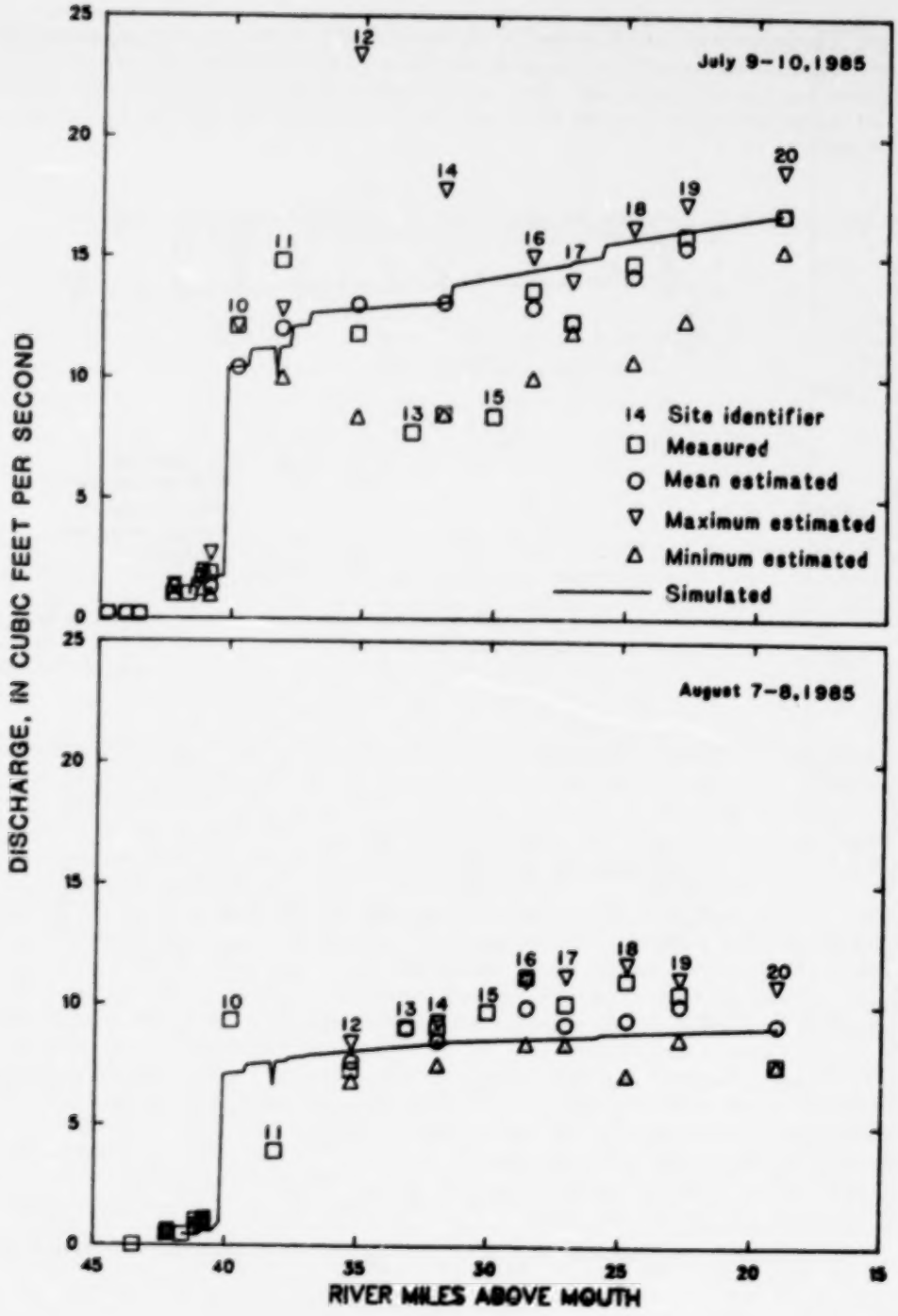


Figure 10.--Stream discharges measured, estimated, and simulated, July 9-10 and August 7-8, 1985.

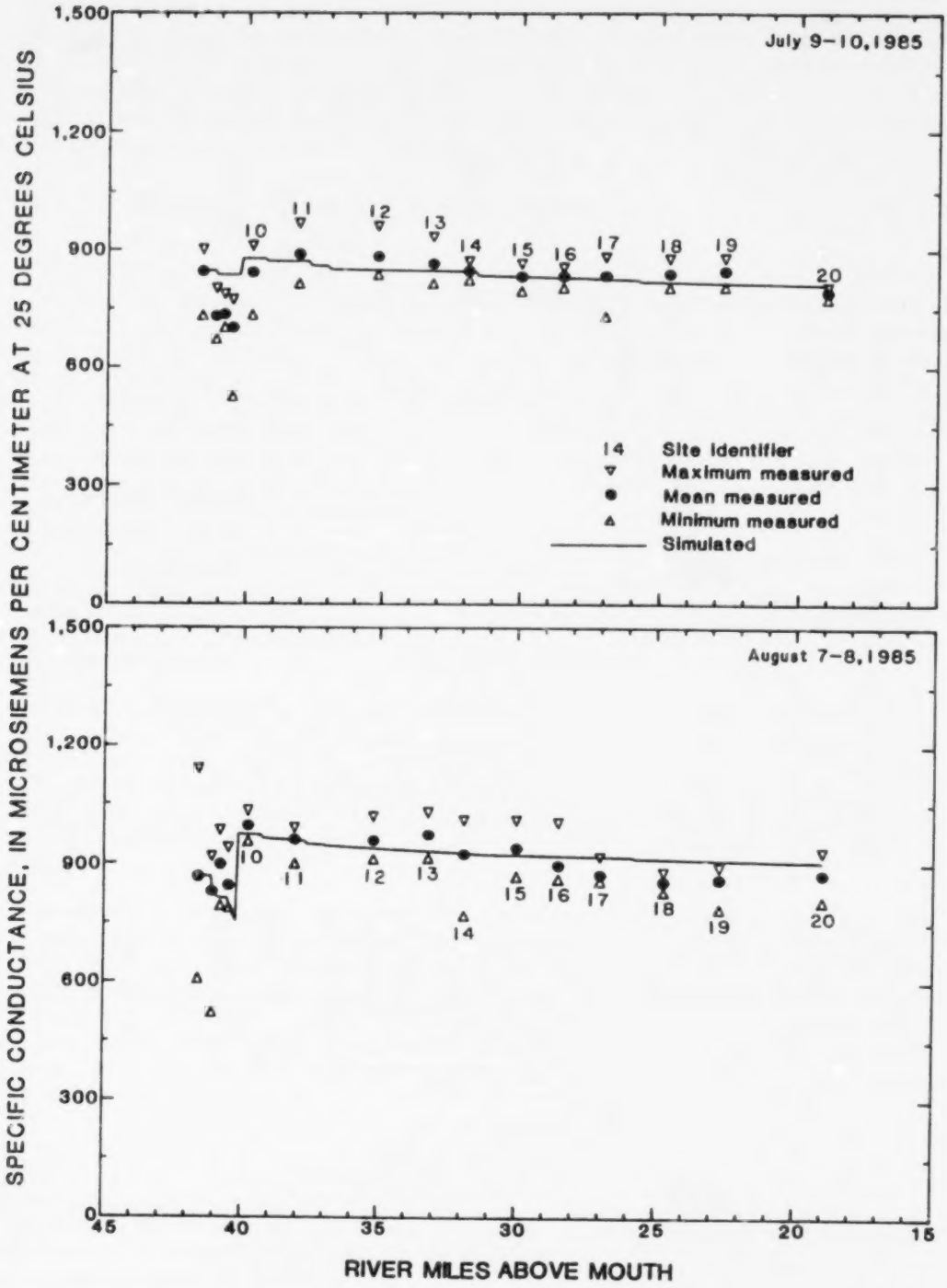


Figure 11.--Measured and simulated specific conductance, July 9-10 and August 7-8, 1985.

Coefficients α_v and β_v were determined from traveltime measurements conducted in the creek for reaches with similar hydraulic characteristics. The coefficients, the reaches to which they apply, and the statistical uncertainty in the estimate of β_v (as determined from the regression) are presented in table 7.

Table 7.--Coefficients, exponents, and errors of estimate for the exponents for the equations used in the model to estimate velocity and depth from discharge

Model reaches	Upstream river mile	Downstream river mile	Velocity equation			Depth equation		
			Coefficient α_v	Exponent β_v	Error in exponent	Coefficient α_d	Exponent β_d	Error in exponent
7-10	41.6	40.2	0.201	0.361	0.092	0.766	0.246	0.066
11-27	40.2	19.0	.163	.432	.047	.403	.435	.045

Depth is an important factor in simulation of algae and DO because it is included in the equations to estimate atmospheric reaeration, light extinction, and algal settling. Depth was simulated using empirical coefficients in the following equation:

$$D = \alpha_d Q^{\beta_d} . \qquad (2)$$

The coefficients α_d and β_d were initially determined based on channel cross-section geometry data obtained during discharge measurements. The cross sections were grouped into reaches with similar hydraulic characteristics, the average depth of each cross section was determined, and regression analyses of depth and discharge were done to determine α_d and β_d for the selected reaches.

Because discharge measurements are made at sections that generally are not representative of the entire reach, the empirical coefficients needed to be adjusted to represent the depth in the reach. To adjust the coefficients to represent the reach average, the ratio of the average reach depth to depth at the measurement sections was assumed to be inversely proportional to the ratio of average reach velocity to velocity at the measurement sections. Regression analyses of velocity with discharge at the measurement sections were used to determine coefficients α_{v_m} and β_{v_m}. Coefficients were developed to relate the velocity at measurement sections to the discharge in the same manner as the depth and the reach velocity equations were developed. Assuming that the width of measurement sections is representative of the reach width, it can be shown that

$$\alpha_{d_r} = \frac{\alpha_{v_m} \alpha_{d_m}}{\alpha_{v_r}} \qquad (3)$$

and

$$\beta_{d_r} = \beta_{v_m} + \beta_{d_m} - \beta_{v_r} \qquad (4)$$

where r and m subscripts indentify coefficients for an entire reach and those specific to measurement sections, respectively. The values for the coefficients relating reach depths to discharge and the reaches for which they apply are shown in table 7.

Algae and Nutrients

Following calibration of the flow and hydraulics, the nutrients (ammonia, nitrite plus nitrate, and phosphorus) and chlorophyll-a (an indicator of algal biomass) were calibrated. Coefficients were estimated from measured data when possible. Coefficients that could not be estimated from the data were initially set to values recommended by model documentation (Roesner and others, 1981) and by modeling references (Bowie and others, 1985). Coefficients that were not defined by measured data and not well defined in the literature were estimated and adjusted to calibrate the model to simulate the measured data.

Algal populations appeared to be small in most of the study area during the diel sampling periods, although the concrete channel through Galesburg was choked with attached aquatic plants. Analyses of water samples for chlorophyll-a indicate that phytoplankton (free-floating algae) populations were sparse in the subreaches of the creek included in the model. However, Butts (1986, p. 4) reports that "a three-mile reach of the creek, starting about two miles below the [Galesburg WWTF] plant is choked with rooted aquatic growth," which agrees with visual observation of the stream. This area would be the model subreach from RM 38.1 to RM 35.2 (between sites 11 and 12).

The QUAL-II model simulates phytoplankton populations based on the chlorophyll-a concentration but does not simulate periphyton and attached plants. The following equations were used to simulate phytoplankton in the model:

$$A = C/\alpha_o \qquad (5)$$

and

$$\frac{dA}{dt} = \mu A - \rho A - \frac{\sigma_1}{D} A \ . \qquad (6)$$

The range for the ratio of chlorophyll-a to algae, suggested by the model documentation, is 20 to 100 micrograms chlorophyll-a per milligram of algae. This ratio was adjusted to 1.2 micrograms chlorophyll-a per milligram algae in an attempt to simulate the effect of some of the attached plants as phytoplankton. Reducing this ratio causes the model to simulate a large quantity of algae for the same concentration of chlorophyll-a measured in the water.

The suggested ranges for algal growth, respiration, and settling rates are 1.0 to 3.0 per day, 0.05 to 0.5 per day, and 0.5 to 6.0 feet per day, respectively. The growth and respiration rates were set to 3.5 and 0.12 per day, respectively. Algal settling rates were varied to calibrate the algal concentrations simulated by the model and ranged from 0.0 to 1.0 foot per day. Again, the growth and settling rates were set outside of recommended ranges in an attempt to simulate the effect of attached plants and periphyton.

Half-saturation constants for nitrogen, phosphorus, and light intensity serve to decrease the algal growth rate in simulations of growth limitation by nutrients or light. The growth rate is decreased based on the following equation:

$$\mu = \mu_{max} \cdot \frac{N}{N+K_n} \cdot \frac{P}{P+K_p} \cdot \frac{K_L + I}{K_L+I(e^{-\lambda D})} \cdot \quad (7)$$

The suggested ranges for the half-saturation constants are 0.2 to 0.4 mg/L for nitrogen, 0.03 to 0.05 mg/L for phosphorus, and 0.03 Langleys per minute for light (Roesener and others, 1981, p. 33). The constants were set to the mid-point of these ranges and sensitivity analyses were performed for the extremes of the ranges.

Light-extinction coefficients determine how much of the available light is lost because of water depth and turbidity. The light-extinction coefficient and the half-saturation constant for light serve to limit the growth based on equation 7. Light-extinction coefficients were estimated from Secchi disk depth by assuming an exponential decay in light intensity, and 10 percent of the surface light intensity remaining at the maximum Secchi depth. Light-extinction coefficients were estimated in this manner from Secchi depths obtained during the July 9-10 and August 7-8 diel sampling periods. The values from both diel sampling periods then were averaged by subreach, and these values were used in the model. Light-extinction coefficients for subreaches 21 and 22 (RM 30.0 to RM 27.0) were increased from the value estimated from Secchi-disk readings because the creek flows through wooded areas in these subreaches that decrease the light available for photosynthesis.

Nutrient concentrations were simulated by considering the effects of algal uptake and respiration, source-sink terms, and for nitrogen species nitrification. The following equations are used by the model to simulate these processes:

Ammonia

$$\frac{dN_1}{dt} = \alpha_1 \rho A - \beta_1 N_1 + \sigma_3 / A_x \; ; \quad (8)$$

Nitrite

$$\frac{dN_2}{dt} = \beta_1 N_1 - \beta_2 N_2 \; ; \quad (9)$$

Nitrate

$$\frac{dN_3}{dt} = \beta_2 N_2 - \alpha_1 \mu A \; ; \quad (10)$$

and

Phosphorus

$$\frac{dP}{dt} = \alpha_2 \rho A - \alpha_2 \mu A + \sigma_2 A_x \; . \quad (11)$$

Coefficients describing the nitrogen and phosphorus content of algae determine how much nitrite plus nitrate and phosphorus concentrations are reduced by photosynthesis and how much ammonia and phosphorus concentrations are increased by respiration and cell decomposition. The recommended ranges for these coefficients are 0.08 to 0.09 milligram nitrogen per milligram algae and 0.012 to 0.015 milligram phosphorus per milligram algae. To calibrate the model, these coefficients were set to 0.12 milligram nitrogen per milligram algae and 0.035 milligram phosphorus per milligram algae, exceeding the recommended ranges in an attempt to force phytoplankton simulation to incorporate the effect of periphyton and attached macrophytes on nutrient concentrations.

Although the specified nitrogen, phosphorus, and chlorophyll-a content and the maximum growth rate exceeded the suggested ranges, the model was unable to simulate the measured nitrite plus nitrate concentrations. Most notably, in the subreaches from RM 38.1 to RM 30.0 (sites 11-15), measured nitrite plus nitrate concentrations decreased sharply, but model simulations showed little or no change in these concentrations, perhaps because of the abundance of rooted aquatic plants in these subreaches, which the model cannot simulate. Sensitivity analyses for these coefficients indicated that the model is insensitive to changes in these coefficients because of the low algae (chlorophyll-a) concentrations.

Nitrification and source-sink coefficients are used to calibrate the nutrients after algal effects are calibrated. The rate at which ammonia oxidizes to form nitrite was estimated by dividing the decrease in total Kjeldahl nitrogen (organic plus ammonia nitrogen) between two sampling sites by the traveltime through the intervening subreach. In the model, ammonia concentrations are decreased by oxidation and settling to the streambed and increased by point sources and ammonia released by algal decay. The method used to estimate the oxidation rate agrees with the model conceptualization provided settling and algal decay are negligible. Positive ammonia-oxidation values estimated from measured total Kjeldahl nitrogen concentrations for the July 9-10 and August 7-8 diel sampling periods ranged from 0.10 to 2.2 per day. Many reaches had negative values, indicating an unidentified source of nitrogen or significant algal decay. For the July 9-10 diel sampling period, the mean value for all subreaches with a positive rate was 1.2 per day. For the August 7-8 diel sampling period, the mean value for all subreaches with a positive rate was 1.3 per day.

The mean of the positive rates from the July 9-10 and August 7-8 diel sampling periods, 1.25 per day, was input to the model as the ammonia oxidation coefficient for all subreaches in the model. The standard deviation of these rates is 0.67. This value was used in analyses of model sensitivity to changes in the ammonia-oxidation rates.

The rate at which nitrite reacts to form nitrate nitrogen was set to 20.0 per day for all subreaches in the model. This is the maximum value recommended in the model documentation and results in all nitrite reacting quickly to form nitrate. By setting this coefficient high, simulated nitrate values correspond to the concentration of nitrite plus nitrate, which is what the water samples were analyzed for. Simulated nitrite plus nitrate concentrations are increased

through nitrification and decreased through algal uptake. Because ammonia concentrations were small relative to nitrite plus nitrate concentrations, the ammonia oxidation rate did not have a significant effect on nitrite plus nitrate concentrations. Algal growth, respiration, settling, and nutrient uptake parameters were used to calibrate for nitrite plus nitrate.

Similarly, phosphorus concentrations in the model are affected by sources to the creek, by uptake and release through algal photosynthesis and respiration, and by settling to and reentrainment from the streambed. Because sources of phosphorus were assumed to be known, phosphorus was calibrated by adjustment of algal coefficients, with final calibration achieved by adjustment of source-sink rates. Rates and coefficients used in the calibrated model to describe algae and nutrient concentrations are listed in tables 8 and 9.

Figures 12 and 13 show simulated and measured chlorophyll-a, phosphorus, ammonia, and nitrite plus nitrate concentrations for the July 9-10 and August 7-8, 1985, diel sampling periods, respectively.

Model-sensitivity analyses indicate that the model is sensitive to changes in the algal simulation coefficients. Although phytoplankton concentrations in the creek were low, model coefficients were adjusted in an attempt to simulate the effect of periphyton and attached plants, which caused model results to be sensitive to algal coefficients. The algal coefficients that have the greatest effect on model results are the algal growth and respiration rates, and the light-extinction coefficients. Coefficients describing the flow velocity and depth also affected the modeled chlorophyll-a concentrations. The largest effect, caused by varying the algal coefficients, occurred at the downstream end of the study reach where chlorophyll-a concentrations were the highest. The model coefficients that had the greatest effect on the simulated algae and nutrient concentrations are listed in table 10 for the July 9-10 diel sampling period and in table 11 for the August 7-8 diel-sampling period.

The July 9-10 and August 7-8 data were simulated without the effect of algae in order to quantify the effect of adjusting algal coefficients beyond recommended ranges to account for the effects of periphyton. Results from these simulations on DO, phosphorus, ammonia, and nitrite plus nitrate concentrations are shown in figures 14 and 15. These simulations show that algae and plants affect nutrient concentrations and that DO concentrations are affected, but the basic shape of the DO concentration profile is not changed. The greatest sensitivity to changes in the algal growth coefficients was at RM 19.0 (tables 10 and 11).

Dissolved Oxygen

Dissolved-oxygen concentrations were used as the primary indicator of water quality in the creek. Of all the constituents modeled in this study, DO is the most complex to simulate. The equation used to estimate change in DO concentrations is

$$\frac{dO}{dt} = K_2 (O^* - O) + (\alpha_3 \mu - \alpha_4 \rho)\Lambda - K_1 L - \frac{K_4}{A_x} - \alpha_5 \beta_1 N_1 - \alpha_6 \beta_2 N_2 \quad . \qquad (12)$$

Table 8.--Coefficients used in the model to simulate algal and nutrient kinetics

Coefficient	Recommended range	Value used
Oxygen production by algae (milligrams oxygen per milligram algae)	1.4 - 1.8	1.4
Oxygen uptake by algae (milligrams oxygen per milligram algae)	1.6 - 2.3	2.1
Nitrogen content of algae (milligrams nitrogen per milligram algae)	.08 - .09	.10
Phosphorus content of algae (milligrams phosphorus per milligram algae)	.012 - .015	.035
Maximum growth rate (per day)	1.0 - 3.0	3.5
Respiration rate (per day)	.05 - .5	.12
Nitrogen half-saturation constant (milligrams per liter)	.2 - .4	.30
Phosphorus half-saturation constant (milligrams per liter)	.03 - .05	.04
Light half-saturation constant (langleys per minute)	.03	.03
Oxygen uptake by ammonia oxidation (milligrams oxygen per milligram ammonia)	3.0 - 4.0	3.43
Oxygen uptake by nitrite oxidation (milligrams oxygen per milligram nitrite)	1.0 - 1.14	1.14

[1] Recommended ranges are taken from the QUAL-II model documentation (Roesener and others, 1981, p. 33).

Table 9.--Reach-dependent coefficients used in the model to simulate algal and nutrient kinetics

[ft/d, foot per day; 1/ft, reciprocal foot; 1/d, reciprocal day]

Model sub-reach	Algae settling rate (ft/d)	Light extinction coefficient (1/ft)	Ammonia oxidation rate (1/d)	Nitrite oxidation rate (1/d)	Source rate for phosphorus (1/d)
7	0.35	1.3	1.25	20	-100
8	.35	1.3	1.25	20	-100
9	.35	1.0	1.25	20	-100
10	.35	1.0	1.25	20	-100
11	.35	1.0	1.25	20	-100
12	.70	1.0	1.25	20	-100
13	1.00	1.0	1.25	20	-100
14	1.00	1.0	1.25	20	-100
15	1.00	1.6	1.25	20	-100
16	1.00	2.1	1.25	20	-100
17	.10	2.2	1.25	20	-100
18	.10	1.8	1.25	20	-100
19	.10	2.3	1.25	20	-100
20	.20	2.3	1.25	20	-100
21	.20	6.0	1.25	20	-100
22	.20	8.0	1.25	20	-100
23	.20	2.9	1.25	20	-100
24	.00	2.9	1.25	20	-100
25	.00	2.3	1.25	20	-100
26	.00	2.3	1.25	20	-100
27	.00	2.3	1.25	20	-100

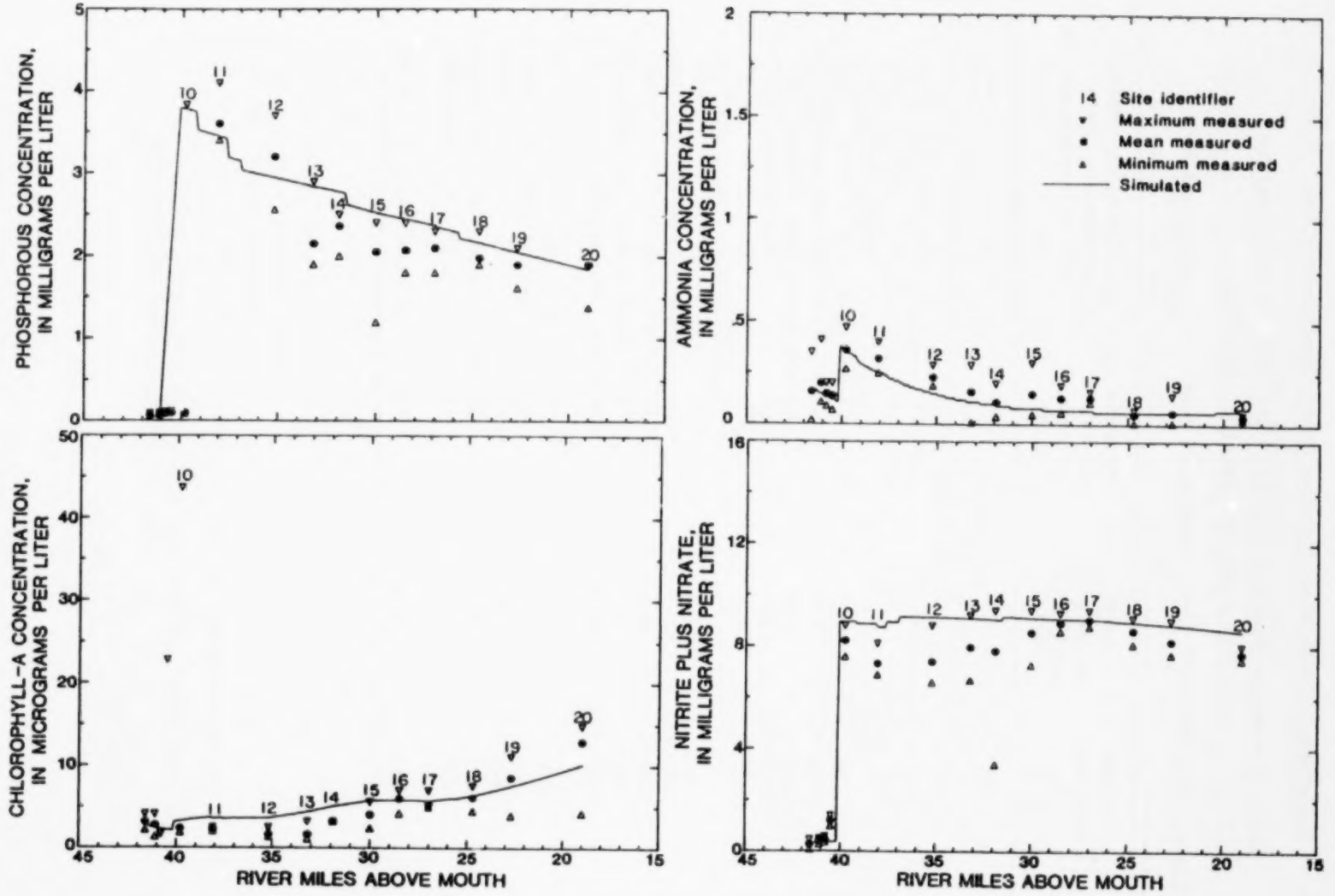


Figure 12.--Measured and simulated concentrations of phosphorus, ammonia nitrogen, chlorophyll-a, and nitrite plus nitrate nitrogen, July 9-10, 1985.

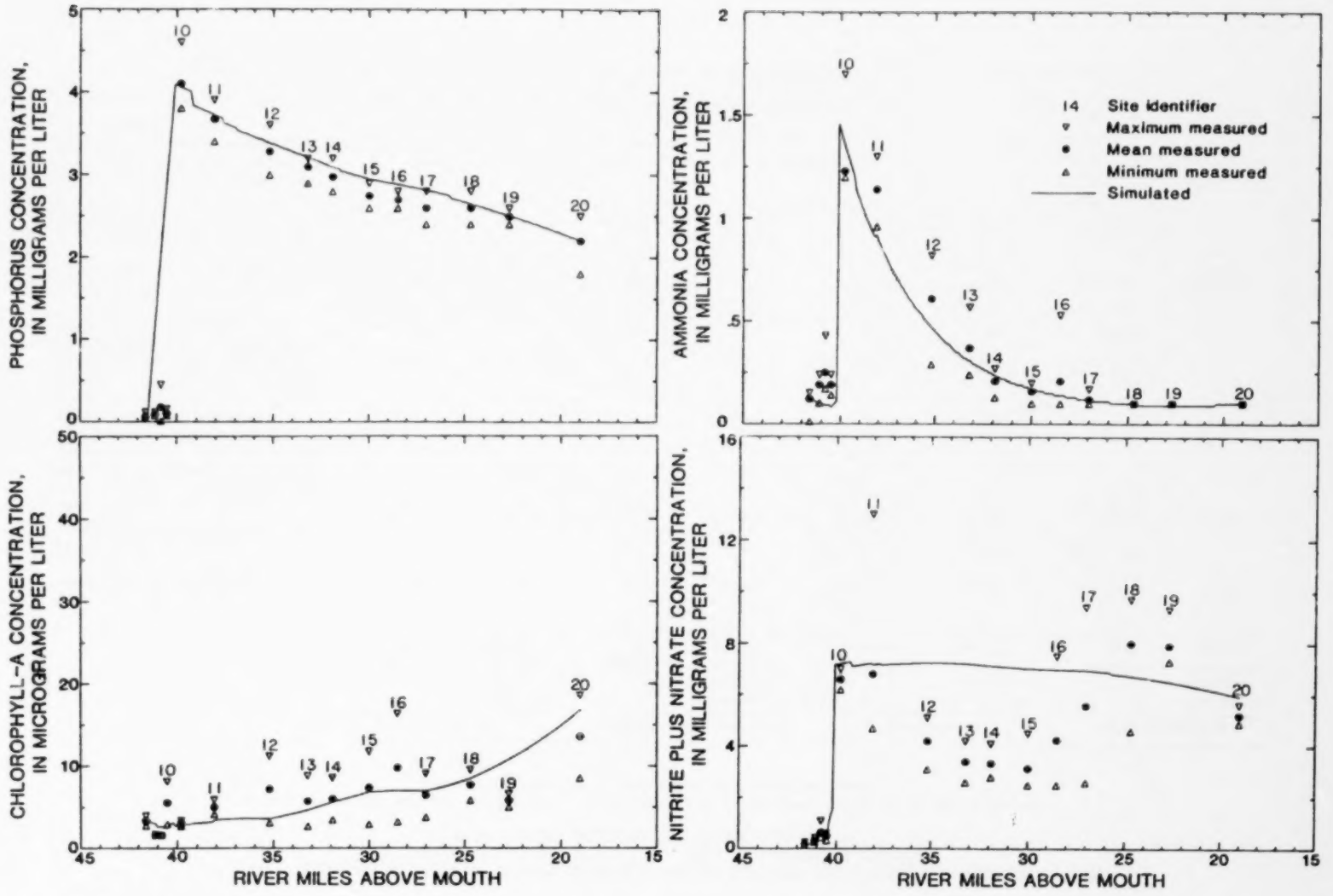

PHOSPHORUS CONCENTRATION, IN MILLIGRAMS PER LITER
AMMONIA CONCENTRATION, IN MILLIGRAMS PER LITER
CHLOROPHYLL-A CONCENTRATION, IN MICROGRAMS PER LITER
NITRITE PLUS NITRATE CONCENTRATION, IN MILLIGRAMS PER LITER
RIVER MILES ABOVE MOUTH
RIVER MILES ABOVE MOUTH
14 Site identifier
Maximum measured
Mean measured
Minimum measured
Simulated

Figure 13.--Measured and simulated concentrations of phosphorus, ammonia nitrogen, chlorophyll-a, and nitrite plus nitrate nitrogen, August 7-8, 1985.

Table 10.--Sensitivity analysis showing maximum change in nutrient and chlorophyll-a concentrations for the model of the July 9-10, 1985, diel sampling period, with changes in model coefficients as shown

[mg/L, milligrams per liter; µg/L, micrograms per liter; RM, river miles above mouth; dashes indicate no change throughout modeled reach]

Change in coefficients	Ammonia		Nitrite plus nitrate		Phosphorus		Chlorophyll-a	
	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (µg/L)
Algal growth rate increased from 3.5 to 4.0 per day	19.0	0.02	19.0	-0.35	19.0	-0.12	19.0	3.77
Algal respiration rate increased from 0.12 to 0.20 per day	19.0	.02	19.0	.17	19.0	.07	19.0	-2.22
Exponent in equation to estimate velocity from discharge increased by one standard deviation (11 percent)	--	--	19.0	.14	19.0	.05	19.0	-1.41
Exponent in equation to estimate depth from discharge increased by one standard deviation (10 percent)	--	--	19.0	.12	19.0	.04	19.0	-1.17
Light extinction coefficient increased by 17 percent	19.0	-.01	19.0	.20	19.0	.07	19.0	-2.17
Algae settling rate increased by 10 percent	--	--	19.0	.04	19.0	.01	19.0	-.54
Ammonia decay rate increased by one standard deviation of the estimated rates (54 percent)	35.2	-.05	35.2	.05	--	--	--	--

Table 11.--Sensitivity analysis showing maximum change in nutrient and chlorophyll-a concentrations for the model of the August 7-8, 1985, diel sampling period, with changes in model coefficients as shown

[mg/L, milligrams per liter; µg/L, micrograms per liter; RM, river miles above mouth; dashes indicate no change throughout modeled reach]

Change in coefficients	Ammonia		Nitrite plus nitrate		Phosphorus		Chlorophyll-a	
	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (µg/L)
Algal growth rate increased from 3.5 to 4.0 per day	19.0	0.04	19.0	-0.78	19.0	-0.26	19.0	8.39
Algal respiration rate increased from 0.12 to 0.20 per day	19.0	.03	19.0	.33	19.0	.13	19.0	-4.07
Exponent in equation to estimate velocity from discharge increased by one standard deviation (11 percent)	19.0	-.01	19.0	.24	19.0	.08	19.0	-2.43
Exponent in equation to estimate depth from discharge increased by one standard deviation (10 percent)	19.0	-.01	19.0	.16	19.0	.05	19.0	-1.57
Light extinction coefficient increased by 17 percent	19.0	-.02	19.0	.38	19.0	.13	19.0	-4.04
Algae settling rate increased by 10 percent	--	-.01	19.0	.10	19.0	.03	19.0	-1.28
Ammonia decay rate increased by one standard deviation of the estimated rates (54 percent)	35.2	-.19	35.2	.19	--	--	19.0	.03

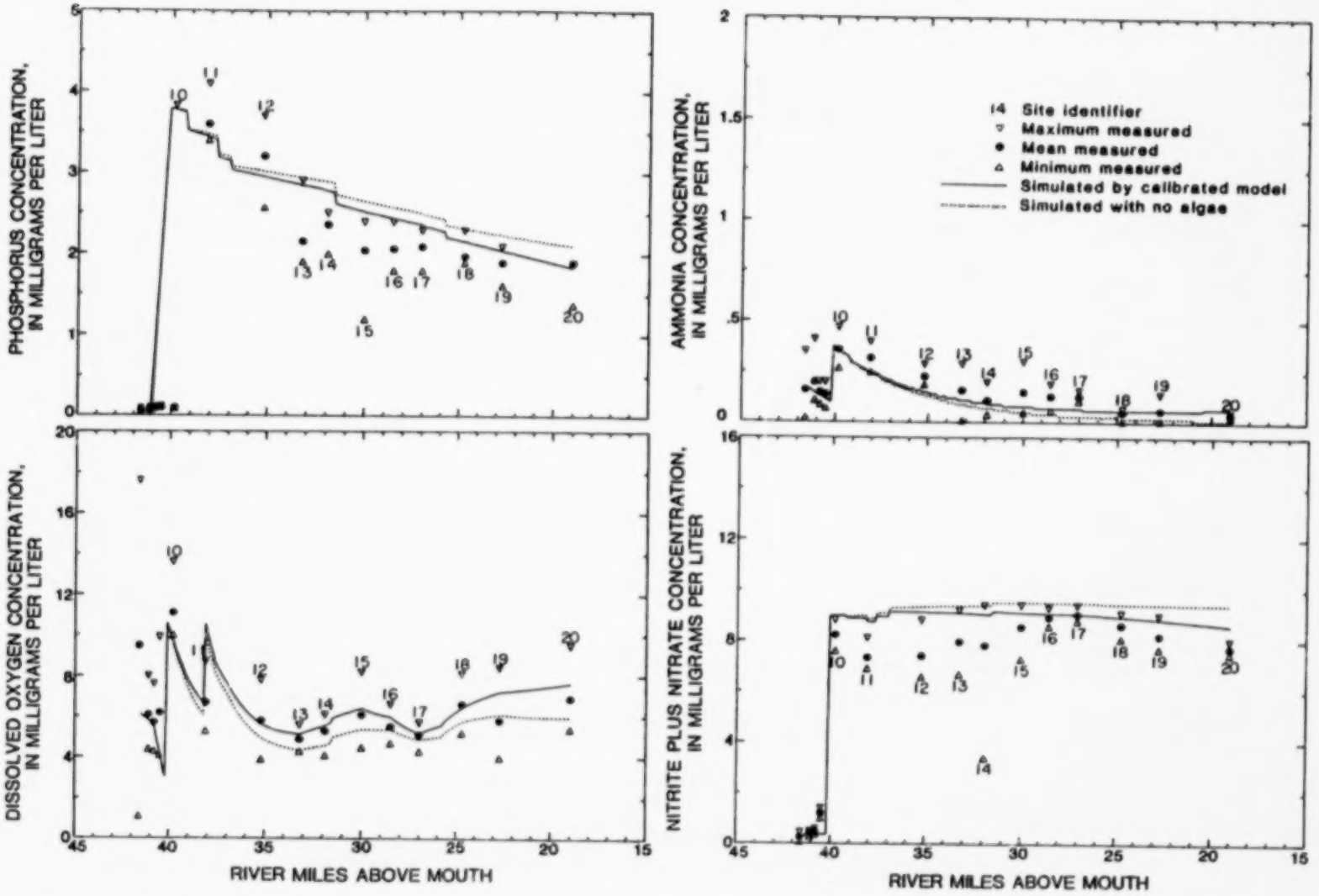

PHOSPHORUS CONCENTRATION, IN MILLIGRAMS PER LITER
AMMONIA CONCENTRATION, IN MILLIGRAMS PER LITER
DISSOLVED OXYGEN CONCENTRATION, IN MILLIGRAMS PER LITER
NITRITE PLUS NITRATE CONCENTRATION, IN MILLIGRAMS PER LITER
RIVER MILES ABOVE MOUTH
RIVER MILES ABOVE MOUTH
14 Site identifier
Maximum measured
Mean measured
Minimum measured
Simulated by calibrated model
Simulated with no algae

Figure 14.--Concentrations of phosphorus, ammonia nitrogen, dissolved oxygen, and nitrite plus nitrate nitrogen, simulated by the model with and without algae, July 9-10, 1985.

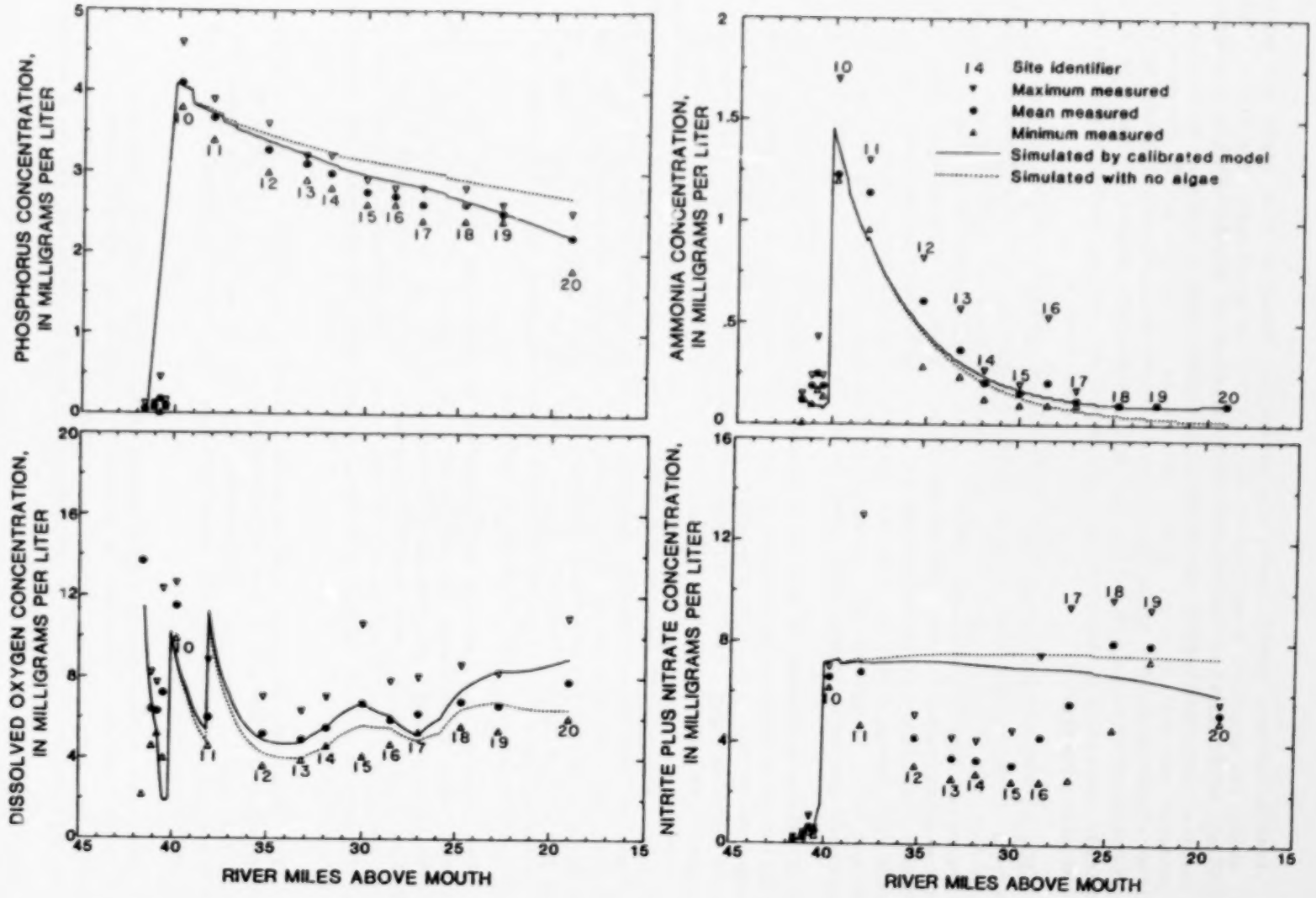

PHOSPHORUS CONCENTRATION, IN MILLIGRAMS PER LITER
AMMONIA CONCENTRATION, IN MILLIGRAMS PER LITER
DISSOLVED OXYGEN CONCENTRATION, IN MILLIGRAMS PER LITER
NITRITE PLUS NITRATE CONCENTRATION, IN MILLIGRAMS PER LITER
RIVER MILES ABOVE MOUTH
RIVER MILES ABOVE MOUTH
14 Site identifier
Maximum measured
Mean measured
Minimum measured
Simulated by calibrated model
Simulated with no algae

Figure 15.--Concentrations of phosphorus, ammonia nitrogen, dissolved oxygen, and nitrite plus nitrate nitrogen measured and simulated by the model with and without algae, August 7-8, 1985.

Reaeration-rate coefficients are estimated, based on flow depth and velocity, using the equation developed by Velz (1970) as previously described. The α_3 and α_4 terms describe the rate of DO production by photosynthesis and uptake by respiration. The ranges for these coefficients are 1.4 to 1.6 milligrams DO produced per unit of algal growth and 1.6 to 2.3 milligrams DO consumed per unit of algae respired. These coefficients were set to 1.4 milligrams DO produced per unit of algae growth and 2.1 milligrams DO consumed per unit of algae respired. Sensitivity analyses were performed by varying these to the extremes of the given ranges.

The α_5 and α_6 coefficients give the oxygen uptake in the nitrification process. These values were set to the stoichiometric equivalent amounts needed to balance the chemical reactions. These rates are 3.43 milligrams DO per milligram ammonia oxidized to nitrite, and 1.14 milligrams DO per milligram nitrite oxidized to nitrate (Bowie and others, 1985, p. 158). Some researchers indicate that these coefficients may be too high because of cell synthesis (Bowie and others, 1985, p. 159) and that these coefficients need to be set to 3.22 and 1.11, respectively. Sensitivity analyses performed by making these adjustment showed no significant changes in the simulated DO concentrations.

Ultimate carbonaceous BOD is a measure utilized to quantify biochemical oxidation of organic constituents in the water. This is a first-order decay process described by a rate constant, K_1. Ultimate carbonaceous BOD is reduced by the decay process, with a corresponding decrease in DO, and by the settling of organic matter to the streambed, which reduces BOD without a corresponding decrease in DO. Increases and decreases in ultimate carbonaceous BOD are simulated by a source-sink term in the model. Increases result from reentrainment of organics from the streambed, periphyton and plants sloughed off by the flow, and other similar sources of organic matter. Ultimate carbonaceous BOD and the decay-rate coefficient were measured from water samples collected at each site and from samples collected at all known inflows to the creek. The mean of the decay rate coefficients measured at two adjacent sites was input as the rate coefficient for the intervening subreach.

The DO model calibration was completed by adjusting the SOD rate coefficient. This coefficient describes the rate at which DO in the water column is used by biological and chemical processes occurring in the streambed. Sediment-oxygen-demand-rate coefficients were initially estimated based on SOD rates measured at selected points in the creek. Adjustments to these rate coefficients were made within the range of measured SOD rates in the subreach being calibrated.

The constants and rate coefficients controlling simulation of ultimate carbonaceous BOD and DO in the calibrated model are listed in table 12. Figures 16 and 17 show the carbonaceous BOD and DO concentrations measured in the creek and simulated by the model for the July 9-10 and August 7-8, 1985, diel sampling periods.

Sediment oxygen demand rates varied widely with location and even in the same cross section. The average standard deviation of SOD measurements in a subreach was 1.40 $(g/m^2)/d$ (grams per square meter per day), which corresponds to an average deviation of 38 percent from the mean measured SOD in a subreach.

Table 12.--Coefficients used in the model to simulate carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations

[(g/ft)/d, grams per foot of reach length per day; 1/d, reciprocal days; all coefficients at 20 degrees Celsius; reaeration rates are base e]

Model sub-reach	Sediment oxygen demand [(g/ft)/d]	Carbonaceous biochemical oxygen demand decay rate		Atmospheric reaeration rate	
		July 9-10, 1985, model (1/d)	August 7-8, 1985, model (1/d)	July 9-10, 1985, model (1/d)	August 7-8, 1985, model (1/d)
7	2,500	0.127	0.108	5.79	7.90
8	3,400	.163	.144	5.49	7.52
9	7,400	.134	.113	5.48	7.38
10	8,800	.134	.072	5.48	6.89
11	7,300	.103	.072	4.36	5.24
12	8,600	.072	.070	9.42	9.50
13	12,000	.115	.084	6.17	6.17
14	8,500	.158	.098	9.50	9.50
15	9,600	.134	.094	6.29	6.28
16	10,600	.134	.094	3.86	4.83
17	10,300	.103	.089	3.78	4.74
18	8,000	.110	.106	3.76	4.69
19	4,800	.185	.132	3.75	4.67
20	4,900	.146	.120	3.63	4.64
21	7,000	.108	.106	3.60	4.62
22	10,000	.130	.130	3.56	4.61
23	7,300	.137	.086	3.51	4.59
24	2,100	.139	.082	3.44	4.56
25	3,700	.142	.079	3.40	4.54
26	5,700	.103	.079	3.36	4.52
27	5,500	.122	.082	3.33	4.50

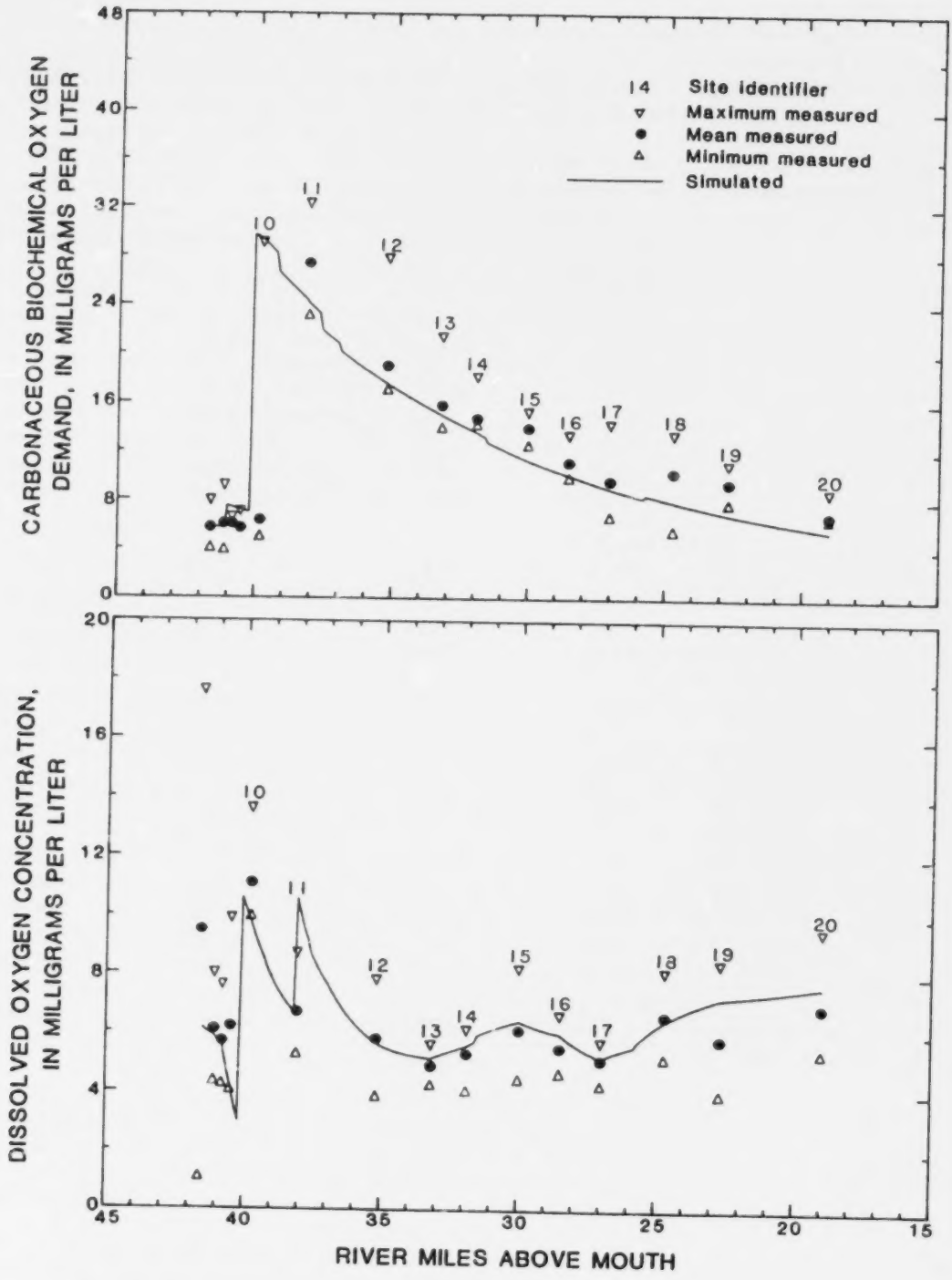


Figure 16.--Measured and simulated concentrations of ultimate carbonaceous biochemical oxygen demand and dissolved oxygen, July 9-10, 1985.

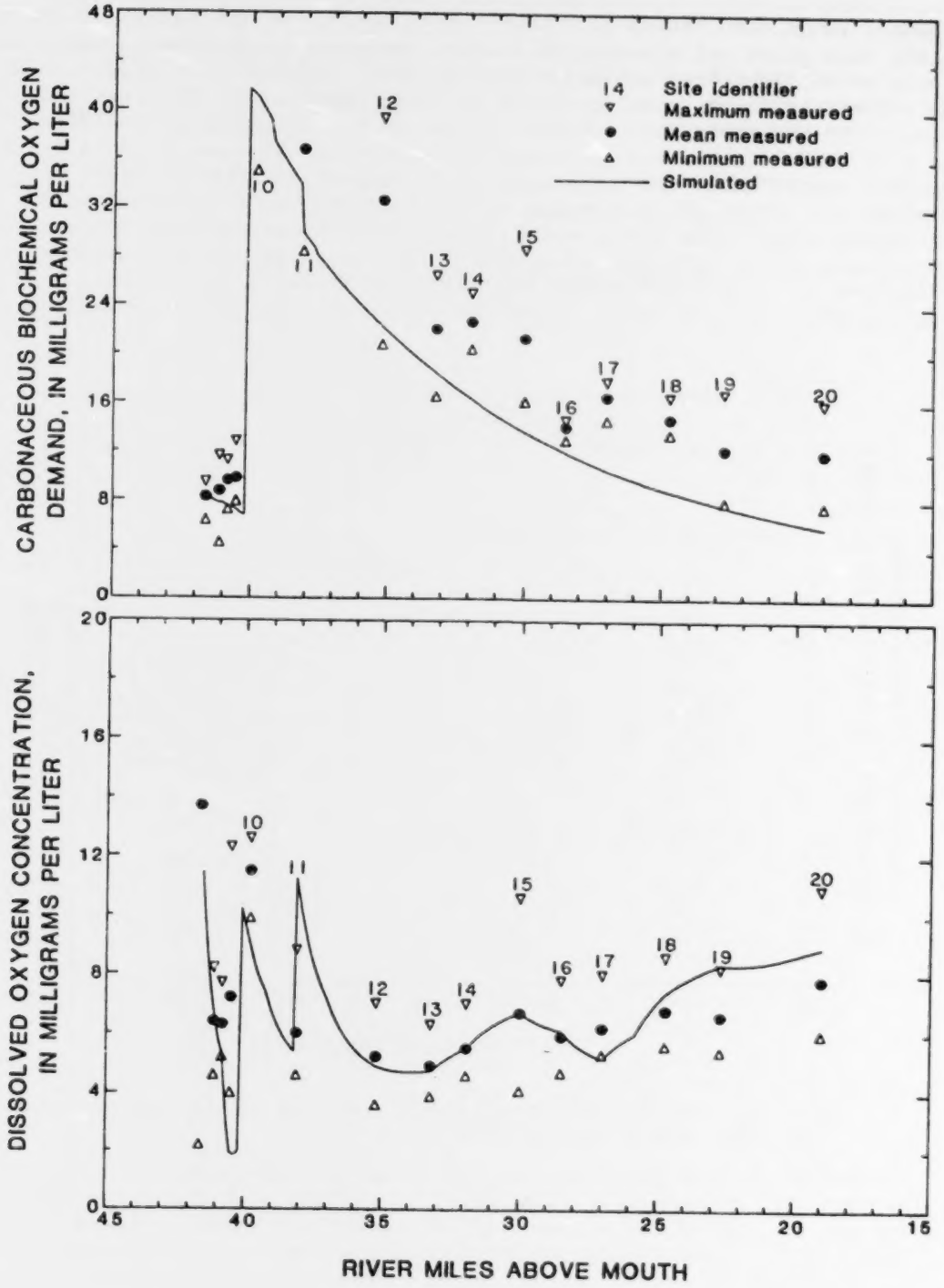


Figure 17.--Measured and simulated concentrations of ultimate carbonaceous biochemical oxygen demand and dissolved oxygen, August 7-8, 1985.

Measured rates also varied with time; thus, making the estimation of subreach values from point measurements difficult. Sediment-oxygen-demand-rate coefficients were, therefore, estimated through model calibration. Figure 18 shows the rates used in the model compared to those measured in the creek and those measured by the State Water Survey (Butts, 1986). Sensitivity analyses for the SOD rate coefficients were performed by varying the SOD coefficients by the standard deviation of the SOD measurements in each individual reach. Figure 19 shows the effect of this change on the simulated DO concentrations for the calibrated model. The model coefficients to which carbonaceous BOD and DO concentrations are most sensitive and the effect on simulated concentrations by changes to these coefficients are listed in table 13 for the July 9-10 diel sampling period and in table 14 for the August 7-8 diel sampling period.

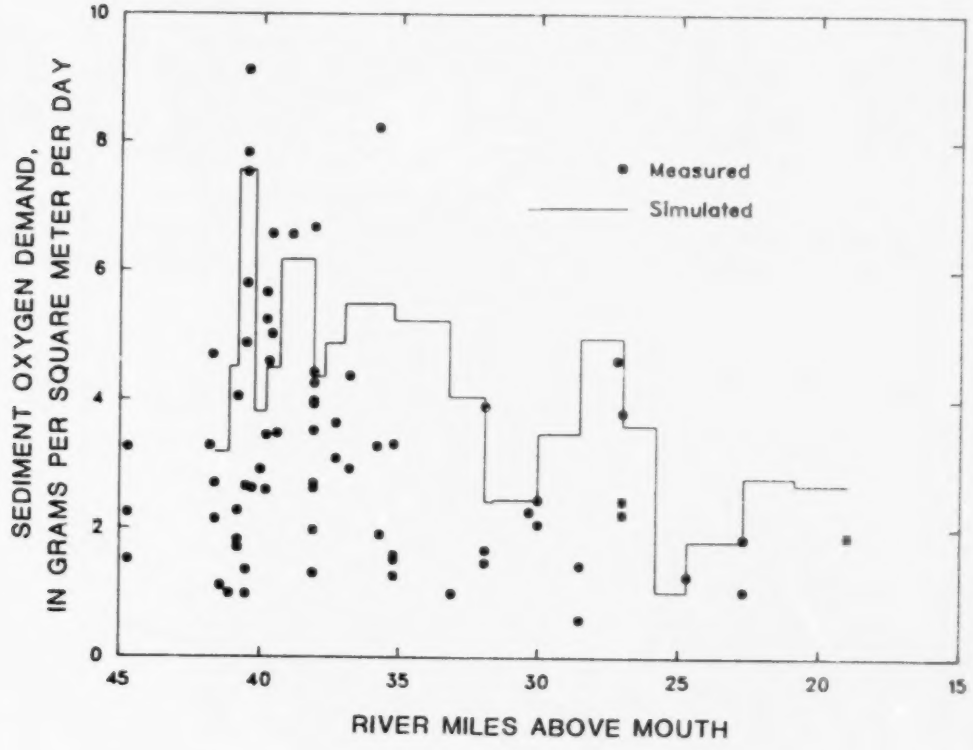


Figure 18.--Measured and simulated sediment oxygen demand.

Rates of many of the reactions affecting modeled constituent concentrations vary with temperature. Simulations were done with the water temperature raised and lowered to the maximum and minimum values measured in each subreach to determine the sensitivity of model results to temperature changes. These simulations showed maximum changes in DO concentrations of 0.4 and 0.8 mg/L for the July 9-10 and August 7-8 diel sampling periods, respectively. For the July 9-10 diel sampling period, the largest change occurred just downstream from the aerator at RM 38.1 and is presumed to be because of a temperature-dependent change in the rate of atmospheric deaeration. For the August 7-8

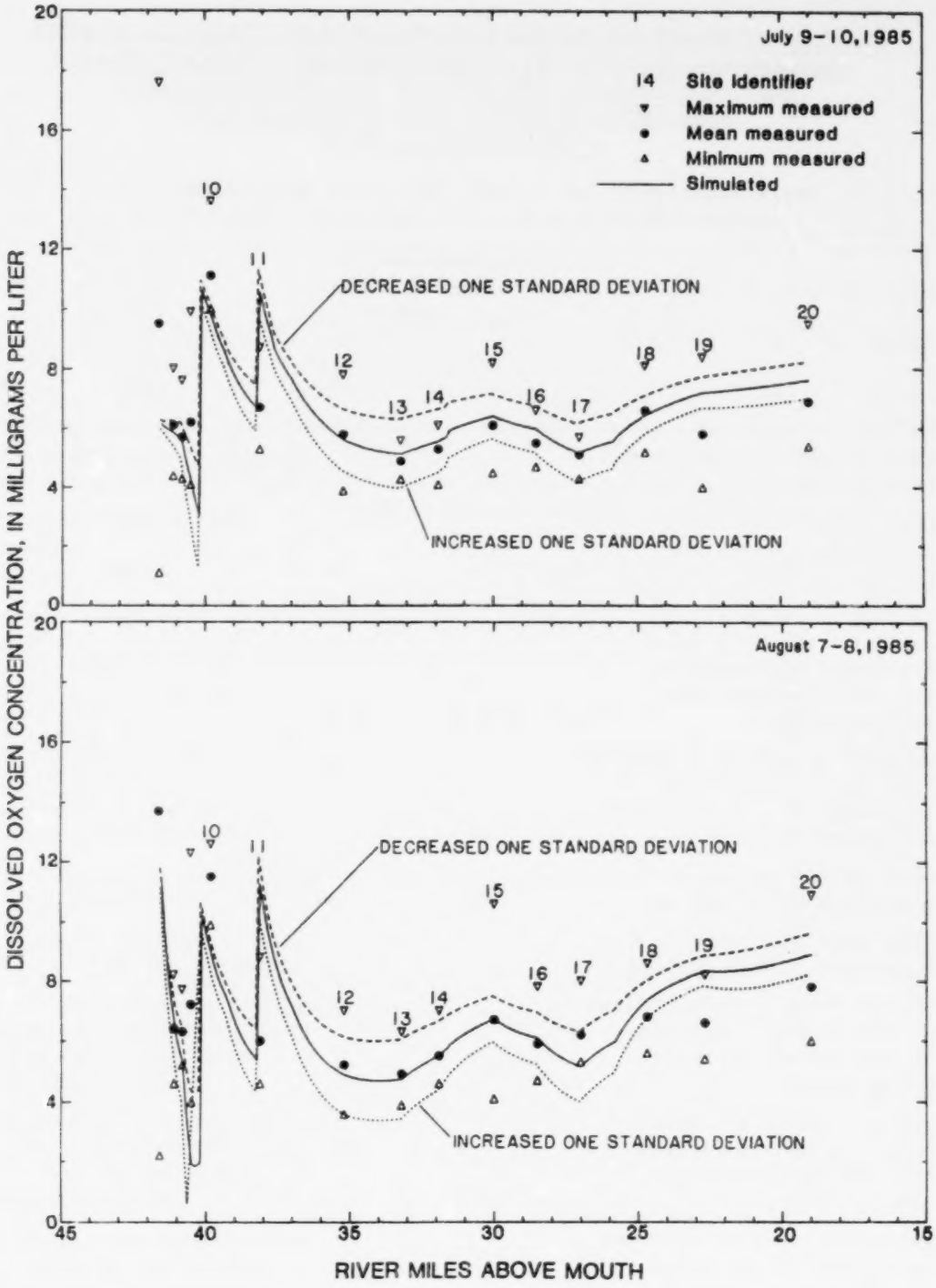


Figure 19.--Concentrations of dissolved oxygen measured and simulated with and without changes in sediment oxygen demand, July 9-10 and August 7-8, 1985.

Table 13.--Sensitivity analysis showing maximum change in ultimate carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for the model of the July 9-10, 1985, diel sampling period, with changes in model coefficients as shown

[mg/L, milligrams per liter; RM, river miles above mouth; dashes indicate no change throughout modeled reach]

Change in coefficients	Carbonaceous biochemical oxygen demand		Dissolved oxygen	
	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (mg/L)
Algal growth rate increased from 3.5 to 4.0 per day	--	--	19.0	1.03
Algal respiration rate increased from 0.12 to 0.20 per day	--	--	19.0	-.74
Exponent in equation to estimate velocity from discharge increased by one standard deviation (11 percent)	24.7	0.94	19.0	-.54
Exponent in equation to estimate depth from discharge increased by one standard deviation (10 percent)	--	--	19.0	-.53
Light extinction coefficient increased by 17 percent	--	--	19.0	-.58
Algae settling rate increased by ten percent	--	--	19.0	-.09
Ammonia decay rate increased by one standard deviation of the estimated rates (54 percent)	--	--	38.1	-.07
Carbonaceous biochemical oxygen demand increased by one standard deviation (28 percent)	24.7	-.57	35.2	-.16
Reaeration rate coefficient increased by one standard deviations (17 percent)	--	--	31.9	.35
Sediment oxygen demand increased by one standard deviation (38 percent)	--	--	31.9	-1.05

Table 14.--Sensitivity analysis showing maximum change in ultimate carbonaceous biochemical oxygen demand and dissolved-oxygen concentrations for the model of the August 7-8, 1985, diel sampling period, with changes in model coefficients as shown

[mg/L, milligrams per liter; RM, river miles above mouth; dashes indicate no change throughout modeled reach]

Change in coefficients	Carbonaceous biochemical oxygen demand		Dissolved oxygen	
	Location (RM)	Change in concentration (mg/L)	Location (RM)	Change in concentration (mg/L)
Algal growth rate increased from 3.5 to 4.0 per day	--	--	19.0	1.86
Algal respiration rate increased from 0.12 to 0.20 per day	--	--	19.0	-1.02
Exponent in equation to estimate velocity from discharge increased by one standard deviation (11 percent)	24.7	1.09	19.0	-.60
Exponent in equation to estimate depth from discharge increased by one standard deviation (10 percent)	--	--	19.0	-.45
Light extinction coefficient increased by 17 percent	--	--	19.0	-.86
Algae settling rate increased by ten percent	--	--	19.0	-.19
Ammonia decay rate increased by one standard deviation of the estimated rates (54 percent)	--	--	38.1	-.24
Carbonaceous biochemical oxygen demand increased by one standard deviation (28 percent)	24.7	-.62	35.2	-.12
Reaeration rate coefficient increased by one standard deviations (17 percent)	--	--	31.9	.45
Sediment oxygen demand increased by one standard deviation (38 percent)	--	--	31.9	-1.79

diel sampling period, the maximum change occurred from RM 19.5 to RM 19.0 and is presumed to be from changed algal growth. These variations were small enough that the diel variation in temperature was not considered to violate the steady-state assumption.

Sensitivity analysis results were used to estimate the relative effect of different processes on DO concentrations. For this analysis, coefficients affecting different processes were increased and decreased by 5 percent, and the changes in DO concentrations with respect to the changes in coefficients were calculated and plotted. The change in DO concentration between the simulations with decreased coefficients and the simulations with increased coefficients gave an estimate of the change in DO with respect to a 10-percent increase in the coefficient. To estimate the effect of photosynthesis and respiration, algal growth and death rates were increased and decreased (independently) by 5 percent, and the resultant changes were summed to estimate a net change in DO because of plant photosynthesis and respiration. The effect of SOD was estimated by the change in DO caused by a 5-percent increase and decrease in the SOD-rate coefficient. The effects of BOD and ammonia oxidation were estimated by the change in DO from a 5-percent increase and decrease in the BOD and ammonia decay-rate coefficients. The effect of atmospheric reaeration was estimated by the change in DO from a 5-percent increase and decrease in the reaeration-rate coefficient.

This analysis is intended to provide a qualitative indication of the relative magnitude of the effects of different processes on DO. This does not quantitatively determine the effect of each process, as comparisons are of both first- and zero-order processes; and interaction effects between processes are not taken into account. Changes in DO concentration resulting from the 10-percent changes in these coefficients are shown in figures 20 and 21 for the models of the July 9-10 and August 7-8 diel sampling periods, respectively. These figures show that SOD is the major oxygen-demanding process occurring in the creek, with the effect distributed throughout the study reach.

Atmospheric reaeration reflects SOD; as SOD increases, reaeration shows a corresponding increase. Net photosynthetic DO production is seen to be the major process increasing DO concentrations in the downstream-most 6 miles of the study reach. Photosynthetic production of DO in the downstream 6 miles may be exaggerated because of first-order algal kinetics (increased growth rates will result in increased algae concentrations, thereby amplifying the effect of the increased growth rate).

The method used to determine the effect of different processes on DO concentrations is not quantitatively exact. However, because of the mathematical formulation of the model, direct calculation of these effects is impossible. The results shown by this analysis agree with indications from sensitivity analyses and with results from simulation of hypothetical situations (discussed later in this report). Therefore, these results are presented as indicators of the importance of different processes on DO concentrations.

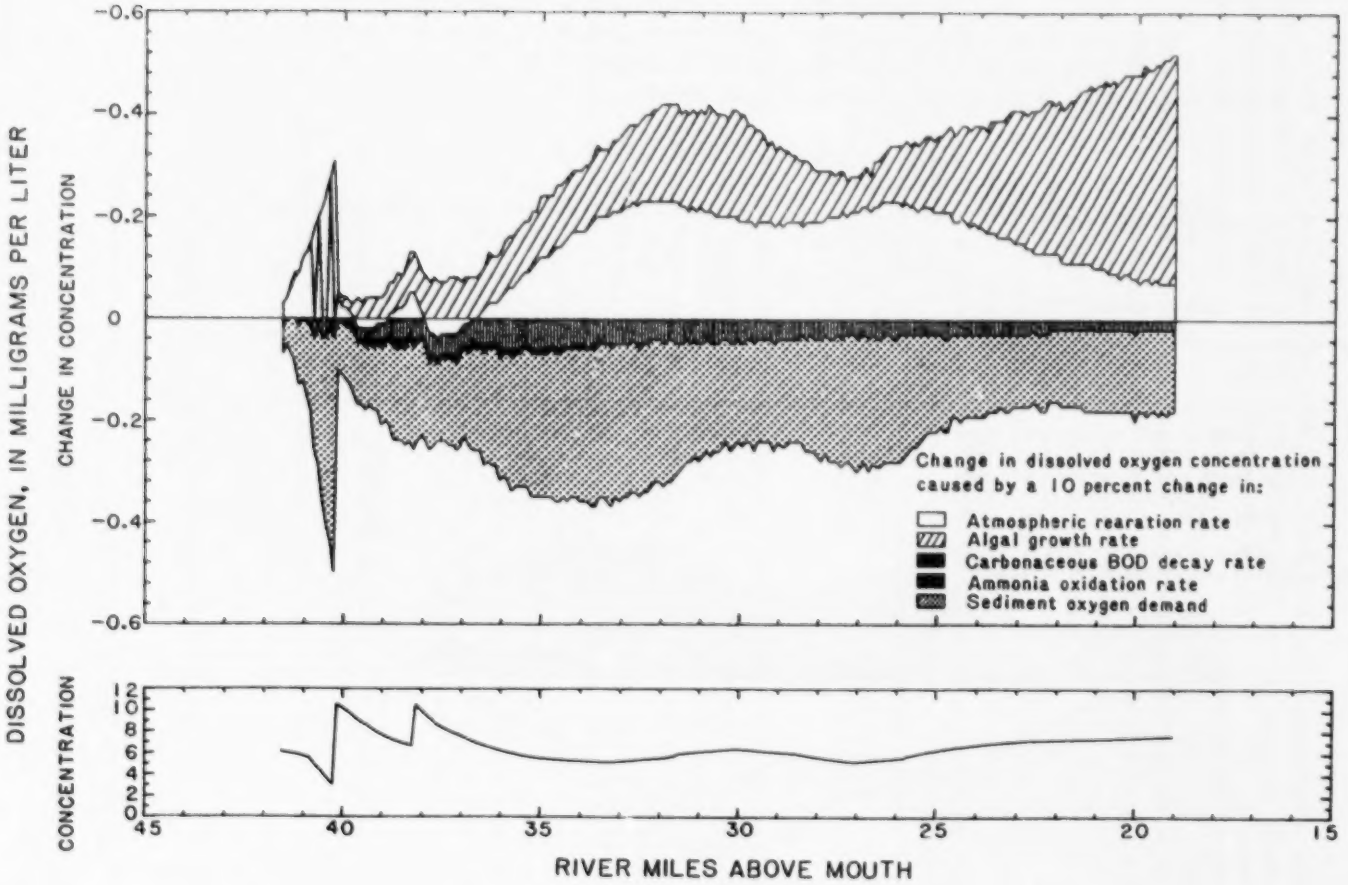


Figure 20.--Change in dissolved-oxygen concentration resulting from 10-percent increases in atmospheric reaeration rate, algal growth rate, carbonaceous biochemical oxygen demand decay rate, ammonia oxidation rate, and sediment oxygen demand, July 9-10, 1985.

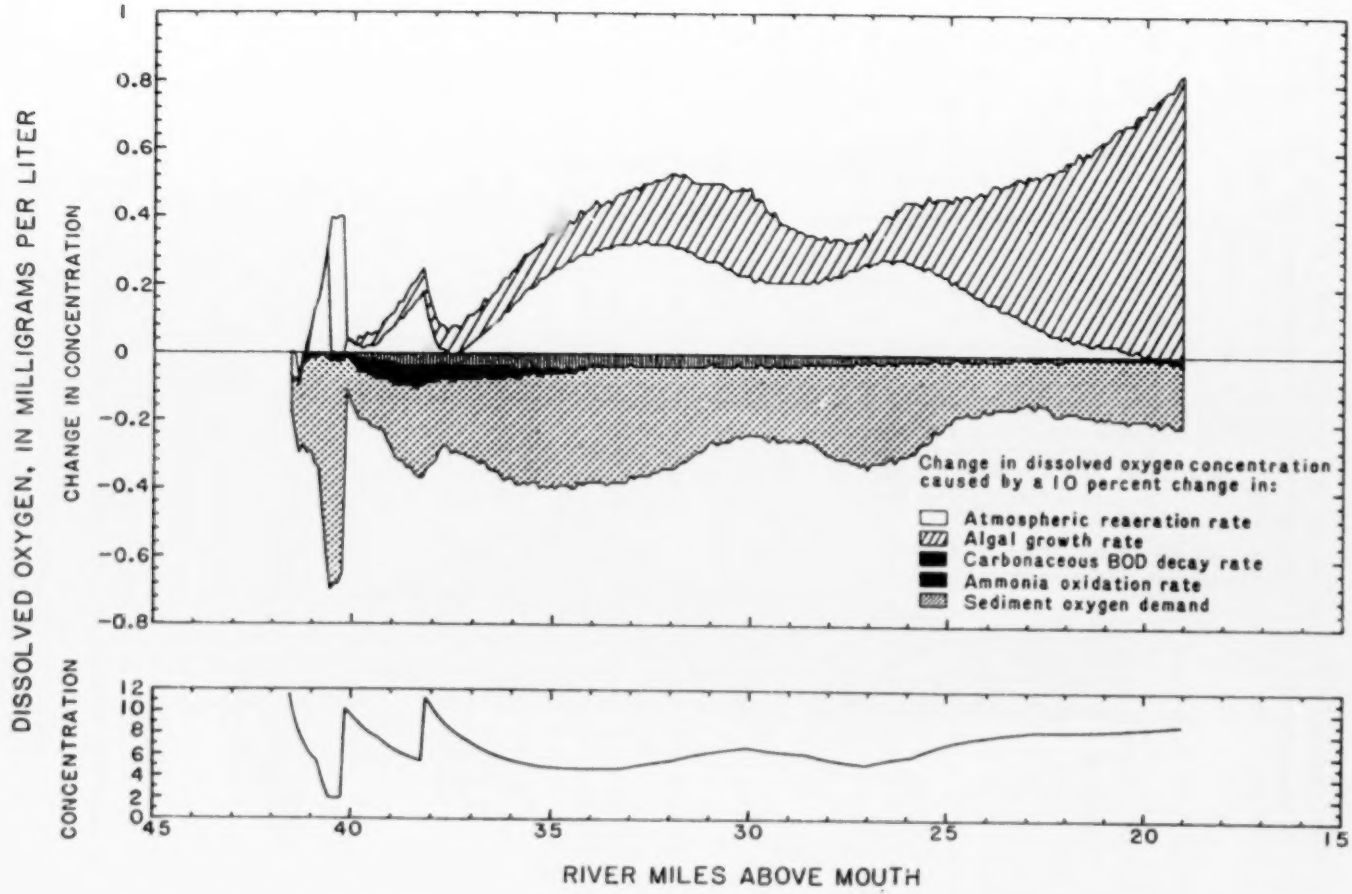


Figure 21.--Change in dissolved-oxygen concentration resulting from 10-percent increases in atmospheric reaeration rate, algal growth rate, carbonaceous biochemical oxygen demand decay rate, ammonia oxidation rate, and sediment oxygen demand, August 7-8, 1985.

Simulation of Hypothetical Situations

After model calibration and verification was completed, the model was used to simulate hypothetical streamflow and water-quality conditions. This demonstrated the possible use of the model as a tool for evaluating different management strategies.

The first hypothetical simulation removed the effect of the aeration systems located at RM 40.2 and RM 38.1, while maintaining all other values from the calibrated model. The aeration systems were removed by eliminating the withdrawal and point-source parameters used to simulate them. Dissolved-oxygen concentrations from this simulation are shown in figure 22, along with the simulated values from the calibrated model for both diel sampling periods. Results indicate the effect of the aerators is limited to about 1 mile downstream from their locations, where they produce increased DO concentrations. Other constituents were not affected by this change. Theoretically, however, significant reduction in DO concentrations could potentially decrease nitrification and SOD rates immediately downstream from the aerators; these secondary effects are probably negligible compared to the DO reduction without the aerators.

The second hypothetical simulation reduced the SOD in all reaches of the creek to a level more representative of the nonurbanized areas of the basin. The SOD for the nonurbanized area of the creek was estimated by averaging the SOD from all the tributaries to the creek; the SOD values in the model were then set to not exceed this average [2.12 $(g/m^2)/d$]. Dissolved-oxygen concentrations from this simulation are shown in figure 23, along with the simulated values from the calibrated models. This simulation resulted in increased DO concentrations throughout the study reach; the DO concentrations are increased the most in subreaches that had the smallest DO concentrations during the diel sampling periods. These simulations indicate that SOD is a principal factor contributing to small DO concentrations measured in the creek, especially in the areas with the smallest DO concentrations. Other constituents were not affected by this change.

The third simulation combined the previous two simulations--SOD was reduced to 2.12 $(g/m^2)/d$, and the aeration systems were removed. Dissolved-oxygen concentrations from this simulation and from the calibrated models are shown in figure 24. This simulation resulted in increased DO in all subreaches except immediately downstream from the aerators. However, even in these subreaches, simulated DO concentrations remained greater than the State standard. Other constituents were not affected by this change.

SUMMARY AND CONCLUSIONS

This report (1) describes the water quality of Cedar Creek near Galesburg, Illinois, during three low-flow periods in the summer of 1985, (2) identifies the Illinois' general-use water-quality standards that were not met during these periods, and (3) presents the methods used and assumptions made in using simulations performed with the QUAL-II model to quantify the processes affecting low-flow water quality in Cedar Creek.

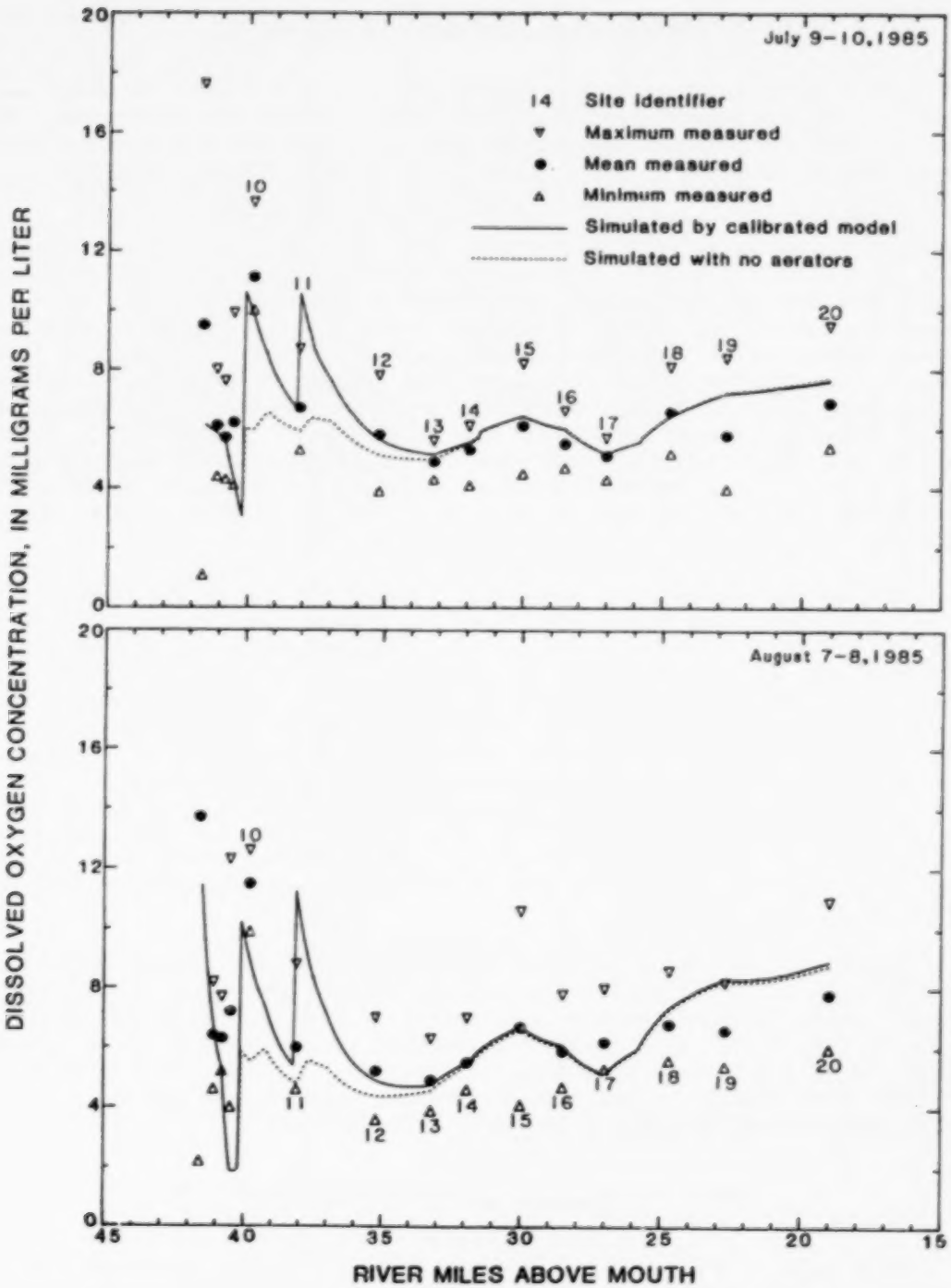


Figure 22.--Concentrations of dissolved oxygen measured and simulated with and without the instream aerators, July 9-10 and August 7-8, 1985.

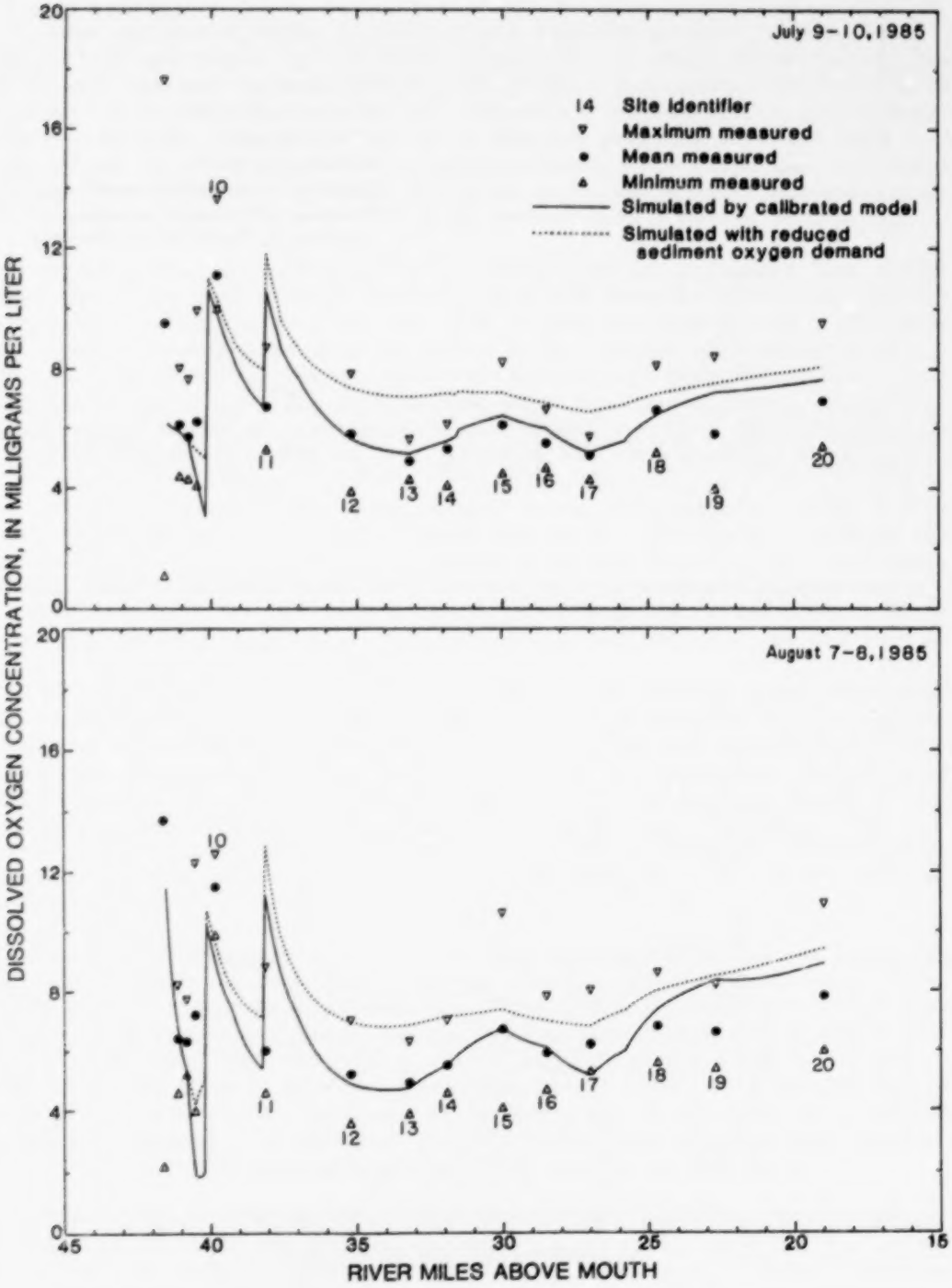


Figure 23.--Concentrations of dissolved oxygen measured and simulated with and without the reduced sediment oxygen demand, July 9-10 and August 7-8, 1985.

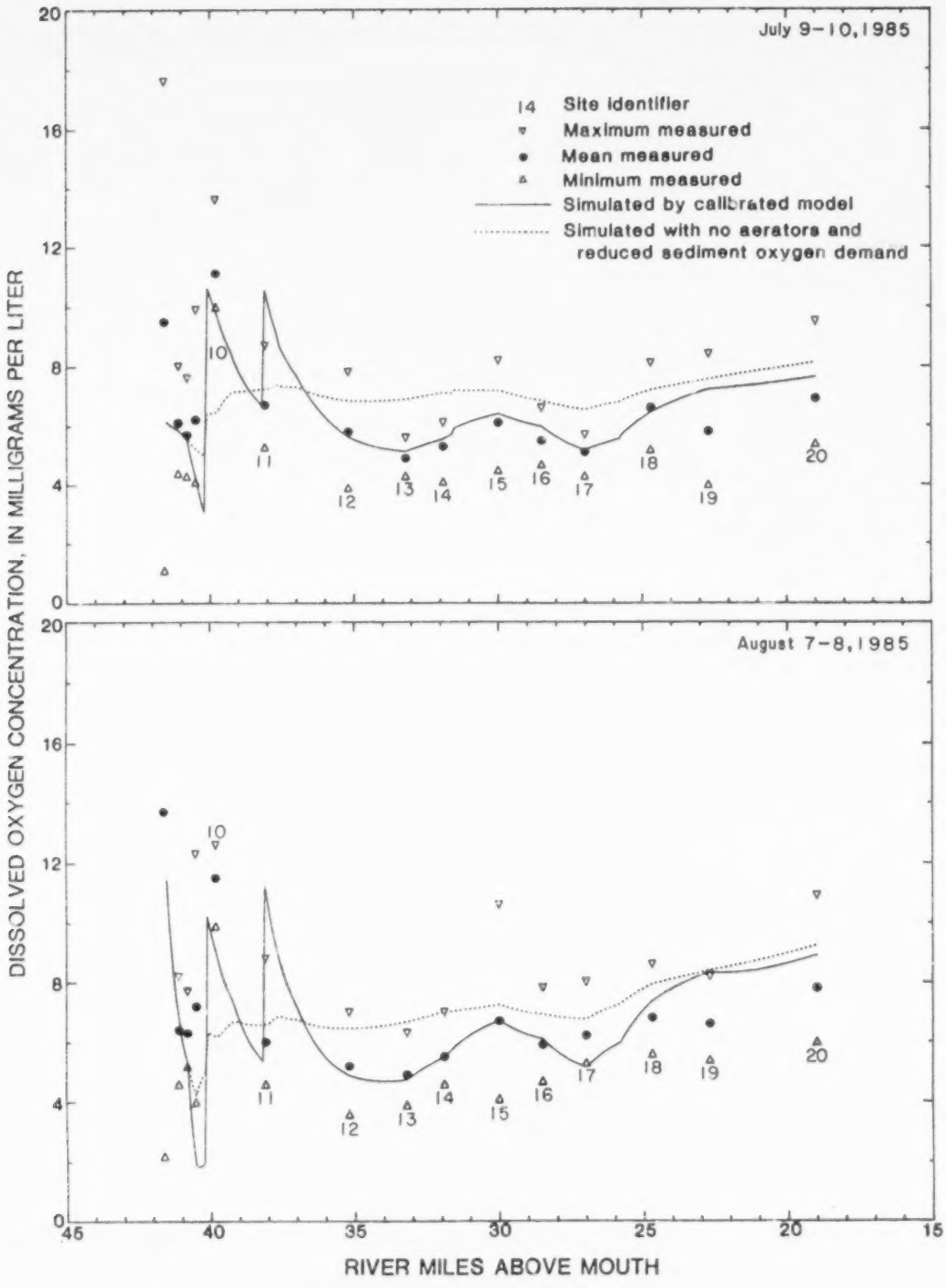


Figure 24.--Concentrations of dissolved oxygen measured and simulated with and without the instream aerators and with reduced sediment oxygen demand, July 9-10 and August 7-8, 1985.

Data collected during 24-hour (diel) sampling periods on July 9-10, August 7-8, and August 27-28, 1985, indicated that State water-quality standards were not met at some sites in the creek. Standards that were not met include dissolved oxygen, which was present in concentrations smaller than the standard at some time during all diel sampling periods; iron and copper, concentrations of which exceeded the standard during the first two diel sampling periods; and manganese, phenol, and total dissolved solids, concentrations of which exceeded the standard during the second diel sampling period.

Results from benthic macroinvertebrate sampling indicated that water in Cedar Creek was contaminated both upstream and downstream from the wastewater-treatment-facility outfall and was most contaminated immediately upstream from the outfall, possibly because of runoff from a sludge-application field located near river mile 40.5. Downstream from the outfall, macroinvertebrate sampling indicated that quality improved rapidly with distance and that, within 10 miles downstream from the wastewater-treatment facility, water quality stabilized at a less contaminated condition than found at any site upstream from this point.

The QUAL-II one-dimensional, steady-state, water-quality model was used to quantify cause-and-effect relations in the creek. The model initially was calibrated to simulate the conditions measured during the July 9-10 diel sampling period. The calibrated model from July 9-10 diel sampling period was used with boundary conditions from the August 7-8 period to verify the ability of the model to simulate conditions other than those for which it was calibrated.

The model was calibrated using the most accurate and reasonable estimates for model coefficients available from the sampling program and the literature. After the model was calibrated, it was used to simulate measured conditions other than those for which it was calibrated. This procedure (model verification) was done to verify the ability of the model to predict low-flow water quality. After model coefficients were calibrated and verified, they were perturbed and the resultant changes in simulated constituent concentrations tabulated to indicate the sensitivity of the model to changes in different coefficients.

Because of the complex interrelations of many of the constituents, some coefficients may not represent the true kinetics of a given process, with the resultant error in simulated concentrations offset by errors in other coefficients. Additionally, some constituent concentrations are so low (notably ammonia nitrogen) that any errors in the coefficients related to it are negligible compared to more dominant processes in the model, such as SOD and plant growth. Therefore, caution needs to be exercised in application of coefficients from the calibrated model to conditions where the dominant processes are different from those used to calibrate and verify the model.

Model simulations required that coefficients describing algae concentration in the creek be set outside recommended ranges to simulate the effect of periphyton and attached plants on DO and nutrient concentrations. Extreme values for some algal coefficients caused model results to be most sensitive to changes in these coefficients. Other coefficients to which the model was sensitive include SOD and coefficients in the equations to estimate velocity and depth from discharge. Model simulations and sensitivity analyses indicate

that SOD and plant photosynthesis and respiration are the factors that have the greatest effect on DO concentrations in the creek. Photosynthesis and respiration effects are limited to the downstream part of the study reach. Model simulations indicate that SOD is the principal factor causing low DO concentrations in many reaches of the creek. Other modeled factors had substantially smaller effects on DO when compared to SOD and plant photosynthesis and respiration.

Model simulations of hypothetical conditions showed the effect of the stream aerators may be limited to about 1 mile downstream from their locations. However, in these subreaches, DO concentrations are higher than without aeration.

Other hypothetical simulations of the July 9-10 and August 7-8, 1985, diel sampling periods were made with SOD reduced to a value representative of nonurbanized portions of the creek. These simulations showed increased DO concentrations in large parts of the study reach, especially in those portions of the creek with the smallest measured DO concentrations.

REFERENCES CITED

Bowie, G. L., Mills, W. B., Porcella, D. B., Campbell, C. L., Pagenkopf, J. R., Rupp, G. L., Johnson, K. M., Chan, W. H., Gherini, S. A., Chamberlin, C. E, 1985, Rates, constants, and kinetics formulations in surface water quality modeling, second edition: U.S. Environmental Protection Agency publication EPA/600/3-85/040, 455 p.

Butts, T. A., 1986, Sediment oxygen demand assessments in Cedar Creek below Galesburg, Illinois: Illinois Department of Energy and Natural Resources, State Water Survey Division, Contract Report 377, 34 p.

Clark, Dietz, and Associates, 1980, Cedar Creek water quality study prepared for the Galesburg Sanitary District: Clark-Dietz Engineers and Midwest Aquatic Enterprises, 60 p.

Clarke, R. P., 1984, Urban runoff, an update on research activities and policy at the Illinois Environmental Protection Agency, in Blake-Coleman, W., ed., Urban effects on water quality and quantity, conference proceedings of October 20 and 21, 1983: Illinois Department of Energy and Natural Resources, p. 25.

Illinois Pollution Control Board, 1986, State of Illinois Rules and Regulations, Title 35: Environmental Protection, Subtitle C: Water Pollution, Chapter I: Springfield, Illinois, 44 p.

MacMullen, M. W., 1984, A perspective on applicable review criteria for potential CSO projects, in Blake-Coleman, W., ed., Urban effects on water quality and quantity, conference proceedings of October 20 and 21, 1983: Illinois Department of Energy and Natural Resources, p. 208.

McCutcheon, S. C. and Jennings, M. E., 1982, Discussion of: Stream reaeration by Velz Method: ASCE, Journal of Environmental Engineering Division, v. 108, no. EE1, p. 218-220.

McFarlane, R. D., Freeman, W. O., and Schmidt, A. R., 1987, Data collection methods and data summary for the assessment of water quality in Cedar Creek at Galesburg, Illinois: U.S. Geological Survey Open-File Report 87-543, 177 p.

National Council of the Paper Industry for Air and Stream Improvement, 1982, The mathematical water-quality model QUAL-II and guidance for its use -- revised version: National Council of the Paper Industry for Air and Stream Improvement, Technical Bulletin no. 391, 37 p.

Rathbun, R. E., 1977, Reaeration coefficients of streams--state-of-the-art: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 103, no. HY-4, p. 409-424.

Roesner, L. A., Giguere, P. R., and Evenson, D. E., 1981, Computer program documentation for the stream quality model QUAL-II: U.S. Environmental Protection Agency publication EPA 600/9-81-014, 225 p.

Schaeffer, O. J., Ettinger, W. H., Tucker, W. J., and Kerster, H. W., 1985, Evaluation of a community-based index using benthic indicator organisms for classifying stream quality: Journal of the Water-Pollution Control Federation, v. 57, 167 p.

U.S. Census Bureau, 1980, General population characteristics for Illinois: U.S. Census Bureau 1980 Census of Population, 488 p.

U.S. Geological Survey, 1979, Land use and land cover, 1974-75, Burlington, Iowa; Illinois; Missouri: U.S. Geological Survey Open-File Report 79-1590-1, Land-Use Series.

Velz, C. J., 1970, Applied stream sanitation: New York, John Wiley and Sons, 619 p.

TABLE 15

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period

```
TITLE01                 STREAM QUALITY MODEL--QUAL-II IL DIST USGS VERSION
TITLE02                  CEDAR CREEK FOR JULY DIEL #1
TITLE03  YES            CONSERVATIVE MINERAL   I    SPCN     UMHO
TITLE04   NO            CONSERVATIVE MINERAL  II
TITLE05   NO            CONSERVATIVE MINERAL III
TITLE06   NO            TEMPERATURE
TITLE07  YES            BIOCHEMICAL OXYGEN DEMAND IN MG/L
TITLE08  YES            ALGAE AS CHL A IN UG/L
TITLE09  YES            PHOSPHORUS AS P IN MG/L
TITLE10  YES            AMMONIA AS N IN MG/L
TITLE11  YES            NITRITE AS N IN MG/L
TITLE12  YES            NITRATE AS N IN MG/L
TITLE13  YES            DISSOLVED OXYGEN IN MG/L
TITLE14   NO            COLIFORMS  IN NO/100 ML
TITLE15   NO            ARBITRARY NON-CONSERVATIVE
TITLE16  YES  NO
ENDTITLE
LIST DATA INPUT
WRITE OPTIONAL SUMMARY
NO FLOW AUGMENTATION
STEADY STATE
DISCHARGE COEFFICIENTS
INPUT METRIC (YES=1)     =                    OUTPUT METRIC (YES=1)    =
NUMBER OF REACHES        =       21.          NUMBER OF JUNCTIONS      =
NUM OF HEADWATERS        =        1.          NUMBER OF POINT LOADS    =     1
TIME STEP (HOURS)        =                    LNTH. COMP. ELEMENT      =
MAXIMUM ROUTE TIME (HRS)=        15.          TIME INC. FOR RPT2 (HRS)=
ENDATA1
O UPTAKE BY NH3 OXID(MG O/MG N)= 3.43   O UPTAKE BY NO2 OXID(MG O/MG N)=
O PROD. BY ALGAE (MG O/MG A)   = 1.4    O UPTAKE BY ALGAE (MG O/MGA)  =
N CONTENT OF ALGAE (MG N/MG A) =  .10   P CONTENT OF ALGAE (MG P/MG A) =
ALG MAX SPEC GROWTH RATE(1/DAY)= 3.50   ALGAE RESPIRATION RATE (1/DAY) =
N HALF SATURATION CONST. (MG/L)=  .30   P HALF SATURATION CONST. (MG/L)=
LIGHT HALF SAT CONST(LNGLY/MIN)=  .03   TOTAL DAILY RADIATION(LANGLEYS)=6
ENDATA1A
```

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period--Continued

```
STREAM REACH      7.RCH= McClure to LinwoodFROM      41.6    TO      41.1
STREAM REACH      8.RCH= Linwood to C2     FROM      41.1    TO      40.8
STREAM REACH      9.RCH= C2 to WWTF bridge FROM      40.8    TO      40.5
STREAM REACH     10.RCH= bridge to effluentFROM      40.5    TO      40.2
STREAM REACH     11.RCH= WWTF to Old PickarFROM      40.2    TO      39.8
STREAM REACH     12.RCH= Old P. to Trib    FROM      39.8    TO      39.3
STREAM REACH     13.RCH= Trib to C3        FROM      39.3    TO      38.1
STREAM REACH     14.RCH= C3 to 2100 Rd TribFROM      38.1    TO      37.7
STREAM REACH     15.RCH= Trib to RR Trib   FROM      37.7    TO      37.0
STREAM REACH     16.RCH= RR Trib to 1650 RdFROM      37.0    TO      35.2
STREAM REACH     17.RCH= 1650 to 1550 Rd   FROM      35.2    TO      33.2
STREAM REACH     18.RCH= 1550 to 1500 (C4) FROM      33.2    TO      31.9
STREAM REACH     19.RCH= C4 to Trib        FROM      31.9    TO      31.6
STREAM REACH     20.RCH= Trib to 1400 Rd   FROM      31.6    TO      30.0
STREAM REACH     21.RCH= 1400 to 1300 Rd   FROM      30.0    TO      28.5
STREAM REACH     22.RCH= 1300 to 1200 +tribFROM      28.5    TO      27.0
STREAM REACH     23.RCH= 1200 to Trib      FROM      27.0    TO      25.8
STREAM REACH     24.RCH= Trib to 1100 (C5) FROM      25.8    TO      24.7
STREAM REACH     25.RCH= C5 to Old Hwy 34  FROM      24.7    TO      22.7
STREAM REACH     26.RCH= Old 34 to RM 20.9 FROM      22.7    TO      20.9
STREAM REACH     27.RCH= Rm20.9 to 05468400FROM      20.9    TO      19.0
ENDATA2
ENDATA3
FLAG FIELD RCH=   7.      5.      1.6.2.2.2.
FLAG FIELD RCH=   8.      3.      6.2.2.
FLAG FIELD RCH=   9.      3.      2.2.2.
FLAG FIELD RCH=  10.      3.      2.2.2.
FLAG FIELD RCH=  11.      4.      6.2.2.2.
FLAG FIELD RCH=  12.      5.      2.2.2.2.2.
FLAG FIELD RCH=  13.     12.      6.2.2.2.2.2.2.2.2.2.7.6.
FLAG FIELD RCH=  14.      4.      2.2.2.2.
FLAG FIELD RCH=  15.      7.      6.2.2.2.2.2.2.
FLAG FIELD RCH=  16.     18.      6.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  17.     20.      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  18.     13.      2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  19.      3.      2.2.2.
FLAG FIELD RCH=  20.     16.      6.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  21.     15.      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  22.     15.      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  23.     12.      6.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  24.     11.      6.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  25.     20.      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  26.     18.      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
FLAG FIELD RCH=  27.     19.      2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.
ENDATA4
```

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period--Continued

```
HYDRAULICS RCH=   7.                .201    .361    .766    .246    .037
HYDRAULICS RCH=   8.                .201    .361    .766    .246    .037
HYDRAULICS RCH=   9.                .201    .361    .766    .246    .037
HYDRAULICS RCH=  10.                .201    .361    .766    .246    .037
HYDRAULICS RCH=  11.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  12.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  13.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  14.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  15.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  16.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  17.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  18.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  19.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  20.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  21.                .163    .432    .403    .435    .037
HPDRAULICS RCH=  22.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  23.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  24.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  25.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  26.                .163    .432    .403    .435    .037
HYDRAULICS RCH=  27.                .163    .432    .403    .435    .037
ENDATA5
REACT COEF RCH=   7.     .1272  0.2     11.                        .001330
REACT COEF RCH=   8.     .1632  0.2     11.                        .001330
REACT COEF RCH=   9.     .1344  0.2     11.                        .000609
REACT COEF RCH=  10.     .1344  0.2     11.                        .000609
REACT COEF RCH=  11.     .1032  0.2     11.                        .000609
REACT COEF RCH=  12.     .0720  0.45     1.     10.                 .000609
REACT COEF RCH=  13.     .1152  0.45     1.      6.                 .000609
REACT COEF RCH=  14.     .1584  0.45     1.     10.                 .000717
REACT COEF RCH=  15.     .1344  0.45     1.      6.                 .000717
REACT COEF RCH=  16.     .1344  0.45    11.                        .000717
REACT COEF RCH=  17.     .1032  0.45    11.                        .000674
REACT COEF RCH=  18.     .1104  0.45    11.                        .000674
REACT COEF RCH=  19.     .1848  0.45    11.                        .000601
REACT COEF RCH=  20.     .1464  0.45    11.                        .000601
REACT COEF RCH=  21.     .1080  0.45    11.                        .000742
REACT COEF RCH=  22.     .1296  0.45    11.                        .000882
REACT COEF RCH=  23.     .1368  0.4     11.                        .000635
REACT COEF RCH=  24.     .1392  0.4     11.                        .000635
REACT COEF RCH=  25.     .1416  0.4     11.                        .000797
REACT COEF RCH=  26.     .1032  0.4     11.                        .000797
REACT COEF RCH=  27.     .1224  0.4     11.                        .00079
ENDATA6
```

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period--Continued

```
ALGAE, N AND P COEF  RCH=   7.    1.2    0.35    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=   8.    1.2    0.35    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=   9.    1.2    0.35    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  10.    1.2    0.35    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  11.    1.2    0.35    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  12.    1.2    0.70    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  13.    1.2    1.00    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  14.    1.2    1.00    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  15.    1.2    1.00    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  16.    1.2    1.00    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  17.    1.2    0.10    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  18.    1.2    0.10    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  19.    1.2    0.10    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  20.    1.2    0.20    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  21.    1.2    0.20    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  22.    1.2    0.20    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  23.    1.2    0.20    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  24.    1.2    0.00    1.25    20.0    0.   -100.0
ALGEA, N AND P COEF  RCH=  25.    1.2    0.00    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  26.    1.2    0.00    1.25    20.0    0.   -100.0
ALGAE, N AND P COEF  RCH=  27.    1.2    0.00    1.25    20.0    0.   -100.0
ENDATA6A
OTHER COEFFICIENTS   RCH=   7.   2500.          1.3
OTHER COEFFICIENTS   RCH=   8.   3400.          1.3
OTHER COEFFICIENTS   RCH=   9.   7400.          1.0
OTHER COEFFICIENTS   RCH=  10.   8800.          1.0
OTHER COEFFICIENTS   RCH=  11.   7300.          1.0
OTHER COEFFICIENTS   RCH=  12.   8600.          1.0
OTHER COEFFICIENTS   RCH=  13.  12000.          1.0
OTHER COEFFICIENTS   RCH=  14.   8500.          1.0
OTHER COEFFICIENTS   RCH=  15.   9600.          1.6
OTHER COEFFICIENTS   RCH=  16.  10800.          2.1
OTHER COEFFICIENTS   RCH=  17.  10300.          2.2
OTHER COEFFICIENTS   RCH=  18.   8000.          1.8
OTHER COEFFICIENTS   RCH=  19.   4800.          2.3
OTHER COEFFICIENTS   RCH=  20.   4900.          2.3
OTHER COEFFICIENTS   RCH=  21.   7000.          6.0
OTHER COEFFICIENTS   RCH=  22.  10000.          8.0
OTHER COEFFICIENTS   RCH=  23.   7300.          2.9
OTHER COEFFICIENTS   RCH=  24.   2100.          2.9
OTHER COEFFICIENTS   RCH=  25.   3700.          2.3
OTHER COEFFICIENTS   RCH=  26.   5700.          2.3
OTHER COEFFICIENTS   RCH=  27.   5500.          2.3
ENDATA6B
```

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period--Continued

```
INITIAL CONDITIONS   RCH=   7.     80.40 7.4010.60      1000.
INITIAL CONDITIONS   RCH=   8.     75.20 7.4010.60      1000.
INITIAL CONDITIONS   RCH=   9.     74.50 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  10.     75.70 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  11.     74.80 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  12.     74.80 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  13.     76.50 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  14.     76.50 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  15.     76.50 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  16.     78.60 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  17.     78.80 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  18.     78.80 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  19.     78.80 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  20.     79.50 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  21.     79.00 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  22.     79.90 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  23.     79.90 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  24.     80.10 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  25.     80.10 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  26.     80.10 7.4010.60      1000.
INITIAL CONDITIONS   RCH=  27.     80.10 7.4010.60      1000.
ENDATA7
INITIAL COND-2 RCH=   7.   3.11    0.06          7.05   0.12
INITIAL COND-2 RCH=   8.   2.44    0.06          7.05   0.12
INITIAL COND-2 RCH=   9.   2.49    0.06          7.05   0.12
INITIAL COND-2 RCH=  10.   2.54    0.06          7.05   0.12
INITIAL COND-2 RCH=  11.   3.10    0.06          7.05   0.12
INITIAL COND-2 RCH=  12.   2.67    0.06          7.05   0.12
INITIAL COND-2 RCH=  13.   2.32    0.06          7.05   0.12
INITIAL COND-2 RCH=  14.   1.71    0.06          7.05   0.12
INITIAL COND-2 RCH=  15.   1.60    0.06          7.05   0.12
INITIAL COND-2 RCH=  16.   1.46    0.06          7.05   0.12
INITIAL COND-2 RCH=  17.   1.15    0.06          7.05   0.12
INITIAL COND-2 RCH=  18.   1.89    0.06          7.05   0.12
INITIAL COND-2 RCH=  19.   2.87    0.06          7.05   0.12
INITIAL COND-2 RCH=  20.   3.27    0.06          7.05   0.12
INITIAL COND-2 RCH=  21.   5.77    0.06          7.05   0.12
INITIAL COND-2 RCH=  22.   6.32    0.06          7.05   0.12
INITIAL COND-2 RCH=  23.   4.97    0.06          7.05   0.12
INITIAL COND-2 RCH=  24.   5.95    0.06          7.05   0.12
INITIAL COND-2 RCH=  25.   6.83    0.06          7.05   0.12
INITIAL COND-2 RCH=  26.   8.15    0.06          7.05   0.12
INITIAL COND-2 RCH=  27.  10.99    0.06          7.05   0.12
ENDATA7A
```

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period--Continued

```
INCREMENTAL INFLOW    RCH=   7.   0.0
INCREMENTAL INFLOW    RCH=   8.   0.0
INCREMENTAL INFLOW    RCH=   9.   0.0
INCREMENTAL INFLOW    RCH=  10.   0.0
INCREMENTAL INFLOW    RCH=  11.   0.0
INCREMENTAL INFLOW    RCH=  12.   .05 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  13.   .11 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  14.   .04 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  15.   .07 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  16.   .16 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  17.   .20 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  18.   .10 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  19.   .06 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  20.   .31 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  21.   .29 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  22.   .29 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  23.   .23 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  24.   .21 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  25.   .38 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  26.   .34 75.5 7.4  7.3  713.
INCREMENTAL INFLOW    RCH=  27.   .36 75.5 7.4  7.3  713.
ENDATA8
INCR INFLOW-2  RCH=   7.
INCR INFLOW-2  RCH=   8.
INCR INFLOW-2  RCH=   9.
INCR INFLOW-2  RCH=  10.
INCR INFLOW-2  RCH=  11.
INCR INFLOW-2  RCH=  12.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  13.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  14.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  15.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  16.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  17.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  18.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  19.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  20.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  21.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  22.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  23.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  24.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  25.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  26.    2.7     0.13          8.6     0.09
INCR INFLOW-2  RCH=  27.    2.7     0.13          8.6     0.09
ENDATA8A
ENDATA9
```

Table 15.--Listing of the input data set for the model calibrated to the data measured during the July 9-10, 1985, diel sampling period--Continued

```
HEADWATER          1.HDW= ONE                          1.03 80.4  6.3 5.75  844
ENDATA10
HEADWATER-2     HDW=   1.   3.09      .16                0.27      .07
ENDATA10A
POINT LOAD     1.PTL= M2                                0.66 75.2 6.10 6.07  850
POINT LOAD     2.PTL= A                                 0.08 67.4 6.3248.76  587
POINT LOAD     3.PTL= WWE                               8.63 72.412.5034.51  886
POINT LOAD     4.PTL= T22                               0.66 73.6 7.50 5.08  762
POINT LOAD     5.PTL= CLW                              -1.00 76.5 6.7023.19  888
POINT LOAD     6.PTL= CL                                1.00 76.555.0023.19  888
POINT LOAD     7.PTL= T23                               0.82 76.5 6.40 5.31  700
POINT LOAD     8.PTL= T24                               0.49 77.2 7.20 7.24  638
POINT LOAD     9.PTL= T25                               0.66 75.7 9.60 6.13  628
POINT LOAD    10.PTL= T26                               0.08 76.1 8.50 7.67  691
POINT LOAD    11.PTL= T27                               0.49 74.8 7.5017.18  677
ENDATA11
POINT LOAD-2    PTL=   1.   1.49      .20                0.40      0.10
POINT LOAD-2    PTL=   2.   0.00      .04                0.46      0.01
POINT LOAD-2    PTL=   3.   3.30      .44               10.73      4.59
POINT LOAD-2    PTL=   4.   4.14      .08                7.45      0.10
POINT LOAD-2    PTL=   5.   2.01      .32                7.33      3.40
POINT LOAD-2    PTL=   6    2.01      .32                7.33      3.40
POINT LOAD-2    PTL=   7.   1.64      .16               12.00      0.09
POINT LOAD-2    PTL=   8.   3.17      .18               14.00      0.12
POINT LOAD-2    PTL=   9.   3.99      .04               12.00      0.05
POINT LOAD-2    PTL=  10.   1.49      .03                8.15      0.12
POINT LOAD-2    PTL=  11.   2.47      .12                8.40      0.10
ENDATA11A
```


☆ U.S. GOVERNMENT PRINTING OFFICE: 1989-644-106/82061

ASSESSMENT OF PROCESSES AFFECTING LOW-FLOW WATER QUALITY OF CEDAR CREEK, WEST-CENTRAL ILLINOIS